FINAL REPORT

DEVELOPMENT AND EVALUATION OF HEAT/IMPACT RESISTANT FABRICS FOR THE NASA TMG GARMENT

By

L. Howard Olson
Principal Investigator

Under

NASA RESEARCH GRANT NAG 2-135

JUNE 1984

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF TEXTILE ENGINEERING
ATLANTA, GEORGIA 30332

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EXECUTIVE SUMMARY

DEVELOPMENT AND EVALUATION OF HEAT/IMPACT RESISTANT FABRICS FOR THE NASA TMG GARMENT (NAG-2-135)

The principle effort of this research was to determine if improvements in thermal properties of the NASA TMG could be obtained through the use of a pile type insulating layer of monolayer construction. The Shuttle TMG has multilayer insulation. Among improvements sought were increased thermal resistance while the TMG was subjected to compressive loading.

The research was carried out as a thesis research project conducted by Linda B. Kimmel. The body of this report is that completed thesis. Experimental research formed the basis for comparative study of alternative insulations. Atmospheric conditions were used for thermal analysis. Conduction through the polymeric material and radiation were assumed to be the main mechanisms for heat transfer.

A cross-section consisting of Gore-Tex fabric outer fabric, a double flocked foam insulation and a lightweight polyester liner gave thermal resistance values of 160% to 360% of those obtained for the shuttle TMG lay-up over the range of compressive loads utilized in this work. Other pile fabrics showed little or no advantage in the unloaded state and less notable advantage under compressive loading.

The technical monitors at NASA Ames Research Center for this work were Dr. Bruce Webbon and Hubert C. Vykukal.

The Evaluation of Pile Fabrics

for Thermal Insulation

as Related to Protective Space Garments

Linda Beth Kimmel

133 Pages

Directed by Dr. L. Howard Olson

A comparative, experimental study of the thermal protective properties of insulation is conducted for application to the NASA Thermal Micrometeoroid Garment (TMG). Flocked and terry pile fabrics are investigated for possible improvement of TMG thermal resistance under compressive loads, and the reduction of garment complexity and weight. Individual insulation layers are selected from among five groups of fabrics on the basis of resistance to compression, comparative thermal measurements and other considerations. Two polytetrafluorethylene (PTFE) fabrics, one Dacron polyester fabric flocked with long and short nylon fibers, one terry cloth, and one double flocked, scrim reinforced foam blanket are compared with the Shuttle TMG fabrics. Composite layups containing the selected fabric plies are compared to the Shuttle multilayer insulation (MLI) cross section. Thermal conductivity, conductance and resistance measurements are obtained using a disc type, flat plate apparatus, incorporating a simultaneous measurement of specimen thickness. Materials are tested thermally as a function of increased loading. These values are compared to the seven layer TMG tested under identical atmospheric conditions. Substantial improvements in thermal

resistance are evident in selected layups, when compared to the TMG cross section tested under the same applied pressures and atmospheric conditions. A reduced scale TMG mock-up demonstrates the feasibility of the flocked foam insulation layup construction. Space simulated environmental testing of alternative pile fabric layups is essential before concluding successful application in the space environment.

THE EVALUATION OF PILE FABRICS
FOR THERMAL INSULATION
AS RELATED TO PROTECTIVE SPACE GARMENTS

Approved:

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Date Approved by Chairman: 5/22/84

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SUMMARY

A comparative, experimental study of the thermal protective properties of insulation is conducted for application to the NASA Thermal Micrometeoroid Garment (TMG). Flocked and terry pile fabrics are investigated for possible improvement of TMG thermal resistance under compressive loads, and the reduction of garment complexity and weight. Individual insulation layers are selected from among five groups of fabrics on the basis of resistance to compression, comparative thermal measurements and other considerations. Two polytetrafluorethylene (PTFE) fabrics, one Dacron polyester fabric flocked with long and short nylon fibers, one terry cloth, and one double flocked, scrim reinforced foam blanket are compared with the Shuttle TMG fabrics. Composite layups containing the selected fabric plies are compared to the Shuttle multilayer insulation (MLI) cross section. Thermal conductivity, conductance and resistance measurements are obtained using a disc type, flat plate apparatus, incorporating a simultaneous measurement of specimen thickness. Materials are tested thermally as a function of increased loading. These values are compared to the seven layer TMG tested under identical atmospheric conditions. Substantial improvements in thermal resistance are evident in selected layups, when compared to the TMG cross section tested under the same applied pressures and atmospheric conditions. A reduced scale TMG mock-up demonstrates the feasibility of the flocked foam insulation layup construction. Space simulated environmental testing of alternative pile fabric layups is essential before concluding successful application in the space environment.

CHAPTER I

INTRODUCTION

Background and Statement of Problem

The fabric cross section of the Thermal Micrometeoroid Garment, commonly called the TMG by NASA, varies historically, but always contains some form of multilayer insulation (MLI) [68]. In this application, MLI refers to alternating layers of highly reflective, low emissivity metallic films and separating spacers. The films reduce thermal radiative gain or loss and the spacers reduce heat transfer by contact conduction [39]. The Shuttle TMG features several reinforced aluminized mylar film layers between inner and outer fabrics. The outer layer is a Gore-Tex, Nomex and Kevlar fabric referred to as Orthofabric. The inner layer, also referred to as the liner, is a neoprene coated nylon ripstop fabric [67]. The primary purpose of the TMG is thermal insulation, although it also protects against abrasion and small, high velocity particles called micrometeoroids [28].

The low thermal conductivity of MLI depends on the lack of contact between adjacent shields, the removal of gas from the voids between them, and the correspondingly small contribution of solid and gas conduction [39]. Therefore, the insulation value of MLI is greatly reduced when the film layers are compressed together, the usual result of externally imposed forces and TMG design or attachment features [19]. These compressive forces may cause heat leaks, defined as heat conduction through the walls of the space suit. Excessive heat leaks may cause discomfort, injury or death to an astronaut [35]. Incidents of thermal discomfort have been reported despite the overall success of the TMG during extravehicular activity (EVA). It appears TMG thermal insulation is adequate when uncompressed but requires improved thermal protection under compressive loads [36].

Thus, the basic objective of this investigation is to provide improved TMG thermal protection under compressive loads, with a reduction in TMG weight and fabrication costs desirable. This study considers a variety of flocked and terry pile fabrics for use in the TMG. A seven total layer MLI cross section is used as a basis for comparison with alternative TMG layups. This effort follows earlier investigations of monolayer pile fabrics for this purpose [67,89] and is sponsored primarily by a grant from the NASA Ames Research Center. Contributions of materials, services and expertise made by industrial organizations are listed in the acknowledgments.

Scope and Objective of Study

This study evaluates the thermal performance of various pile fabrics for insulation in the TMG. The experimental program includes ten double flocked, scrim reinforced foams sold commercially as blankets, a total of 28 flocked specimens representing flock and substrate variables, and 12 terry cloth specimens varying by weight, construction and pile configuration.

Individual fabrics and composite layups are compared to the Shuttle TMG fabrics during two phases of testing. The first phase obtains fabric thickness of individual plies as a function of pressure.

The effects of pile diameter, pile height, pile density and surface structure on fabric compressibility are considered. The second phase measures thermal transmission properties of individual and multiple ply cross sections. Selected layups are tested for thermal conductivity, thermal conductance and thermal resistance over a range of applied surface pressures.

Thermal tests are performed under atmospheric conditions, using a flat plate, disc type apparatus which provides for simultaneous measurement of specimen thickness. Candidate plies from each group of fabrics are selected on the basis of physical and aesthetic properties. Layups are tested sequentially over a range of increasing loads. All measurements are reported at equilibrium, with one boundary maintained at 100°C and a constant temperature gradient across the specimen. Specimens achieve thermal equilibrium within an hour of pressure adjustment. Thermal data are compared to the seven total ply TMG cross section, tested under identical conditions.

Introduction to Thermal Insulation of Fabrics

Thermal protective garments retard the flow of heat between boundary surfaces in order to maintain thermal comfort for the wearer. Many factors contribute to the thermal insulation of fabrics. Fabric thickness and density are emphasized in the textile literature, in association with the amounts of air entrapped by fabric structure. However, both are a function of applied surface pressure. The end use application influences the relative significance of other factors. Thermal protection is provided by individual fabrics or combinations of textile materials. Composite cross sections may reflect an acceptable compromise between ideal physical, chemical and mechanical properties when no single fabric provides adequate protection [11].

At present, there is no universal method for measuring thermal insulation, and universally applicable insulation values have yet to be established. Investigators must derive or borrow applicable experimental techniques using various existing standards. Interlaboratory tests on identical fabric specimens have produced different thermal insulation values in similar ranking order [102]. Variation derives from contributing factors, differing tests methods, and unique experimental conditions. Units of thermal insulation include reciprocal values of heat transmission and heat resistance. The British Thermal Unit or BTU is generally used by engineers, while physicists and physiologists prefer the calorie. Other terms such as the clo and the tog have also been used [71].

The complexity of heat transfer mechanisms requires experimental measurements of thermal insulation systems. Glaser recommends that new insulation for space be tested initially for thermal conductivity, but emphasizes that results must be interpreted as an estimate of insulation performance when the test environment deviates from space conditions [39]. This investigation uses the seven layer TMG cross section for qualitative comparison of thermal properties measured under atmospheric conditions. Consequently, readers are cautioned against assuming adequacy of thermal protection prior to thermal tests representative of actual radiant loads, micrometeoroid and particulate or ionizing fluxes, and environmental pressure.

Basic Heat Transfer in Fabrics

The three modes of heat transfer, conduction, convection and radiation, are governed by two fundamental principles of thermodynamics. The first law states that energy is not created or destroyed in non-relativistic systems. The second law claims that heat always flows from regions of higher temperature to regions of lower temperature. Temperature is defined as a measure of average kinetic or molecular activity. Heat is the result of this motion and is measured in BTU's, the engineering measure in English units. The BTU is defined as the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit. The term heat transfer refers to the rate at which heat is transferred between objects and is measured in BTU's per unit time. Under atmospheric conditions, heat transmission through textiles involves conductance through the solid fibrous material in series with the conduction, convection and radiant transfer through its pores [70].

Conduction describes the transfer of heat between materials in direct physical contact. A temperature gradient within the material results in an energy transfer rate as defined by Fourier's Law:

$$\dot{q} = \frac{k\Delta T}{L} \tag{1}$$

where: $\dot{q}$ = heat transfer rate (BTU/ft^2-hr)

k = thermal conductivity (BTU/ft-hr°F)

ΔT = temperature difference between boundaries (T_1-T_2, °F)

L = material thickness (feet)

This expression defines thermal conductivity (k) as a property of the intervening medium, and requires an assumption of homogeneity when applied to textiles. Expressions such as effective, equivalent, apparent or over-all conductivity are used to acknowledge convective and radiative contributions to heat transfer. The comparable term, thermal transmission, is preferred as less ambiguous [71]. These terms refer to the combined rate of heat transfer across a unit area of material per unit temperature gradient, and may be reported as the K factor. Division by the total material thickness gives the thermal conductance, or the C factor. The inverse of C is known as the resistance, or the R value, representing a common measure of resistance to the transfer of heat. R value has units of hr-ft^2-°F/BTU and is currently a widely used measure of insulating value. Conduction of heat is proportional to the temperature drop across a material and inversely proportional to its thickness.

Convection is similar to conduction, but involves heat transfer by the expansion and associated circulation between solid surfaces and fluid mediums. There is no convection in the absence of a fluid in the vacuum of space [39].

Radiation involves the transfer of energy between two bodies separated in space, and occurs independent of an intervening medium. It is related to the temperature and the nature of the surfaces. The governing equation involves the difference between the fourth powers of the absolute temperatures of the objects and the emissivity of the radiating surface.

$$\dot{q} = \sigma\varepsilon(T_1^4 - T_2^4) \tag{2}$$

where: $\dot{q}$ = heat transfer rate (BTU/ft^2-sec)

σ = Stefan-Boltzmann constant (0.1714×10^{-8} BTU/hr-ft^2-°R^4)

ε = emissivity of the radiating surface ($0 < \varepsilon < 1$)

T_1 = absolute temperature of the source (°R)

T_2 = absolute temperature of the receiver (°R)

Emissivity is defined as the total heat lost per unit time through a unit area of surface of a body, and is roughly a measure of the efficiency with which the source releases its radiant energy. Radiation absorbing materials increase heat transfer. Reflecting materials may reradiate and functionally reduce radiative heat transfer. The application of these principles to the TMG is discussed in Chapter II.

CHAPTER II

LITERATURE SURVEY

Thermal Measurement Methods

The methods of measurement of thermal insulation can be broadly divided into four categories [66]:

A. Disc methods

B. Rate of warming or cooling methods

C. Constant temperature methods

D. Other methods

Test methods may also be classified by the flat, spherical or cylindrical shapes of the test chamber [39]. Some test methods apply to solid slabs of material and others simulate garment conditions. Descriptions of the measurement categories follow, with examples of each.

Disc Methods

The disc method measures the steady state rate of heat flow through a fabric when placed between two metal plates at different temperatures. It presumes homogeneity of the specimen, demands time consuming tests, and yields pressure dependent values. It is, nonetheless, a common approach.

Disc type methods are used by many researchers in many forms. Methods include the Lees Disc apparatus, modifications of the Cenco-Fitch apparatus, and guarded hot plate techniques. The approach yields the thermal conductivity of Fourier's equation.

The Lees Disc apparatus secures a fabric specimen between two plates and a heating coil, and suspends it in a constant temperature enclosure until equilibrium is achieved. Baxter [8] and Marsh [66] describe early experiments.

Hercus and Laby employ an apparatus containing hot and cold plates with an integral center plate and guard ring assembly. Heat is transmitted through the material when placed between the plates [8].

Griffiths and Kaye place samples on either side of a heated block. The current and applied potential is measured by a potentiometer, and energy passing through them is measured by a water flow method. Temperatures are measured using thermocouples and specimen thickness is measured under specified pressures. Staff uses a similar method. Both experiments are described by Marsh [66].

Speakman and Chamberlain [90] obtain more refined measurements with thermostatically controlled hot and cold plates. A measure of total heat loss is reported instead of thermal transmissibility.

Hollies et al. [52] perform experiments using a Cenco-Fitch assembly with modifications to incorporate two metal plates. Thermal measurements are made at known plate separations over a range of pressures.

Monego [70] uses the Schiefer Compressometer and a modified Cenco-Fitch apparatus to obtain thermal transmission measurements for established thicknesses and pressures. Weiner and Shah [100] also use a modified Cenco-Fitch unit.

Hoge and Fonseca [51] use a guarded hot plate type apparatus which measures thickness within a closed chamber. A hand wheel is used to apply pressure to a layer of fabrics, permitting a series of thermal measurements over a range of thicknesses.

Hoffmeyer [50] uses vertically oriented hot and cold plates to avoid any compressive effects of gravity. A calibrated rack and pinion device controls plate separation to establish fabric thickness and exerted pressure.

Rate of Warming or Cooling Methods

Rate of warming or cooling methods usually measure the rate of cooling of a heat source covered with a fabric specimen, whose outer surface is exposed to the air. A common example of this method is the traditional Cenco-Fitch apparatus. Haven [66] uses a rate of cooling method to measure the relative warmths of blankets in early experiments. Black and Matthew [16] use a Hill's kathathermometer to express heat insulating values as a ratio required for covered and uncovered thermometer bulbs to cool a specified amount. The rate of cooling approach is the simplest, and results in experimental carelessness among certain investigators. Marsh [66] describes some of these early efforts, which date to the turn of the century.

Constant Temperature Methods

Constant temperature methods measure the electrical input required to maintain a fabric insulated body at a constant temperature. The approach establishes the quantity of heat escaping through a fabric covering, and is considered by some to be the most precise technique in a convective atmosphere.

Haven is among the first workers to use the constant temperature method. A temperature controlled, electrically heated cylinder is wrapped in fabric, the end-caps are insulated, and the electrical input is measured. Micrometer readings of the material thickness are provided. This work is described by Illingworth [54].

Sale and Hedrick [84] consider conductive, convective and radiative contributions to heat transmission through fabrics. Fabric thickness is measured with a needle gage. Temperatures are obtained by thermocouples using the potentiometer method, and results are expressed as thermal resistance.

Floyd and Baker [33] utilize an oil-filled cylinder containing a heating coil and report a percentage energy savings or protective ratio for covered versus uncovered cylinders.

Marsh [65,66] reports an empirical quantity called the Thermal Insulating Value (T.I.V.) derived by placing a fabric sleeve between concentric cylinders of different temperatures.

Baxter and Cassie [9] use a surface electrically heated to a constant temperature within a controlled enclosure. The effects of transmissivity and surface emissivity are considered.

Speakman and Chamberlain [90] measure the heat transmitted through a sample in thermal units based on Bunsen's ice calorimeter principle instead of electrical energy units.

Several investigators report on the thermal transmission of blankets. Among these are Schiefer [86] and Gilmore and Hess. The latter uses a Cenco-Fitch apparatus combined with a constant temperature water calorimeter [71].

Other Methods

The last category includes tests that exhibit characteristics of more than one classification and methods that are distinguished from all of them. Several such early efforts are described by Marsh [66]. Thomas notes the effect on heat loss in passing superheated steam through insulation packed concentric shells. Lewis measures the heat insulation of cotton and wool blankets on a weight to weight basis, as measured by energy input with voltmeters and ammeters. Gregory [42] tests clothing for transmission and reflection of heat from a radiant source.

Rees [77] designs an apparatus which measures temperature at equilibrium based on the principle that for conductors in series, the ratio of the temperature drop across them equals the ratio of their thermal resistances. A material of known thermal resistance is used in series with the specimen to establish an R value for the unknown.

Stoll et al. [92] measure heat transmission characteristics in terms of the physiological effects of exposure. Other studies which fall under this classification include Perkins [76], Baitinger [7] and Benisek [14].

The American Society for Testing and Materials (ASTM) methods are mentioned here although some fit other classifications. The primary method recommended by ASTM for measuring heat transfer in fibrous materials is the disc type, guarded hot plate method C177. ASTM recommends this method for determining the thermal conductivity of homogeneous materials in the form of flat slabs. ASTM method C158 is known as the heat flow meter, and uses standard specimens tested by the guarded hot plate method for calibration. The guarded hot box technique, ASTM method C230, is designed to measure thermal conductance and thermal transmittance for nonhomogeneous panels [38]. ASTM test D1518 for thermal transmittance of textile fabrics has been found to be of little value to researchers, due to problems with repeatability and inaccuracy. For this reason, Federal Test Methods Standard 191 has not adopted a similar standard [74].

Relevant Textile Literature

Experimenters attempt to correlate the insulation values of textiles with fabric thickness, weight, density, porosity, moisture content, surface character and fiber type. G. J. Morris [71] identifies 12 factors that influence the thermal insulation of garment fabrics. These are often interrelated and are difficult to discuss separately. The relative significance of contributing factors varies by application, although fabric thickness and density consistently emerge as dominant factors.

The lack of standardization among thermal test methods contributes to inconsistent values of thermal transmission. Winston and Backer [102,103] summarize an ASTM administered interlaboratory study in which all cooperating facilities use constant temperature test methods. Agreement between absolute test values is limited, although comparative rankings of specimens between laboratories is excellent. Fabric thickness is identified as the only property with an important bearing on thermal insulation, and is deemed an adequate prediction of insulation performance. The findings demonstrate the risk of comparing absolute insulation values obtained from different sources.

Thermal insulation improves with increasing fabric thickness, and is influenced by all factors which affect thickness [102]. The mechanical properties of fibers contribute to insulation by influencing loftiness and thickness of the fabric. Weave configuration contributes as correlated with fabric thickness and air entrapment [90]. In general, material thickness is the primary factor when fabric densities are fairly comparable. When material thicknesses are the same, density is identified as the controlling factor [16]. Hoffmeyer [50] uses multivariate analysis to demonstrate that thickness has more significance on thermal resistance than density.

Fabric thickness is measured many ways by different researchers. Sale and Hedrick [84] use a needle gauge of known dimensions. Hess et al. [48] use a micrometer microscope. Speakman and Chamberlain [90] use a micrometer gauge to measure the differential distance to a test platform, with and without a specimen in place. Schiefer [85] designs a Compressometer to measure fabric thickness under known pressures. This instrument uses a rack and pinion mechanism to exert pressure on the specimen. Other researchers use the Compressometer with or without modifications. Careful measurements of fabric thickness are important because of the compressibility of textiles. The surface pressure exerted should be specified when fabric thickness is reported. Speakman and Chamberlain [90] stress that fabric thickness should be measured *in situ* at the time of thermal conductivity measurements.

Many researchers identify fabric thickness as the prime factor influencing the thermal resistance of single plies and report this relationship as essentially linear. These investigators include Speakman and Chamberlain [90], Marsh [65], Rees [77,78], Schiefer [85,86], Peirce and Rees [75], Winston and Backer [102,103], Bogaty and Hollies [17,18], Morris [72], Monego [70], and Weiner and Shah [100]. The individual studies relate to fibrous battings, woven fabrics, and fabric laminated with foam. Monego [70] identifies the latter as superior to fabric structures for air entrapment.

Heat transmission through fabrics is largely dependent on the resistivity of the air which comprises a major proportion of their volume [8]. Black and Matthew [16], Speakman and Chamberlain [90] and Peirce and Rees [75] are among the many researchers who demonstrate that insulation ability is more dependent on the air space than on the nature of the fiber. The conductivity of all fibrous material is greater than that of stationary air [78]. Finck [30] reports that as the density of fibrous material approaches zero, the conductivity approaches that of an air space of comparable thickness. Baxter and Cassie [9] contend that the most efficient insulation for clothing of a given weight has minimum bulk density.

Certain researchers report maximum insulation values associated with particular fiber densities. Peirce and Rees [75] report that heat transfer in fabrics is mostly by conduction, with small contributions from convection and radiation. In general, low density fabrics have a higher resistance than high density materials, as the latter exhibit larger proportionate losses to conduction. The maximum insulation value is attributed to the onset of air immobilization, at which convection is suppressed [51]. The increasing application of pressure reduces this air space, increasing fiber conductivity thereafter [70]. Rees [78] reports an optimum density between 0.03 and 0.06 g/cm^3 (1.87 and 3.75 lb/ft^3). G. J. Morris [71] reports a critical density at about 0.06 g/cm^3 or 3.75 lb/ft^3. Monego [70] reports that Burton witnesses a maximum density around 4 lb/ft^3 for optimum insulation.

Several studies investigate the relationship between fiber orientation and the thermal insulation of fabrics. Finck [30] reports that fixed densities of fibers aligned parallel to the flow of heat have maximum thermal conductivity values two to three times greater than the minimum values associated with arrangement perpendicular to heat flow. Bogaty et al. [18] report that fabric conductance is less dependent on fiber contributions when fibers are aligned parallel to the fabric surface, and perpendicular to heat flow. Fabric conductivity increases when the proportion of fibers aligned perpendicular to the fabric surface and parallel to heat flow increases. Random fiber arrangement exhibits conductive effects intermediate to parallel and perpendicular fiber orientations [78]. Finer fibers offer more resistance to heat flow per unit thickness [93]. Hess, Floyd and Baker [48] note that cotton, flannel and wool pile fabrics have higher insulation values when exposed nap or pile surfaces are directed away from the body rather than towards it.

Fiber orientation in fabrics changes under compression and may result in a change in thermal conductivity. Reduced insulative values are primarily associated with compressed fabric thickness, but may be influenced by changes in fiber alignment. Smooth fabrics exhibit little change in fiber arrangement under pressure, and any increase in fabric conductivity is attributed to an increase in fabric density. However, the fibers of fuzzy surfaced fabrics are flattened during compression. Bogaty et al. [18] attribute the unusually small change in thermal conductivity of fuzzy fabrics between 0.002 and 1.000 psi to the effects of reorientation upon compression. The authors contend that fiber realignment more parallel to the fabric surface counteracts the effects of increased bulk density. The bending stiffness of the fibers, a function of fiber modulus of elasticity and denier, contributes to the deformation response [49]. Generally, an increase in the modulus of elasticity of insulation components results in a decrease in heat transfer [39].

A few investigators have examined the relationship between fabric thickness and the amount of surface pressure applied. Hoffman and Beste [49] suggest an exponential thickness-pressure function for fabrics. A Compressometer with electronic improvements is used to improve on Peirce's thickness formula at low pressures. The compression process changes from one involving superficial surface hairs to one affecting the fabric bulk with increasing pressure. Bogaty et al. [17] identify a parameter obtained from a hyperbolic representation of a thickness-pressure curve and relate it to the hairiness of a fabric. The value varies directly with the height and density of the surface fibers and inversely with their bending stiffness. The value is increased with napping and decreased with shearing, and appears to be additive for multiple ply assemblies. These findings may relate to the flocked pile and terry cloth fabrics considered for the TMG in this investigation.

The researchers identify several mechanisms operating during various stages of compression, including the collapse of fibers normal to the fabric surface as columns, the bending of surface fibers as beam elements and the bending of fiber segments in the yarn against resistance due to crimp and inter-fiber friction. Surprisingly low values of this parameter are reported for the compression of velveteen, which is a cut pile fabric. Instead of a large numeric value characteristic of hairy surfaces, the uniform pile height produces a non-hairy effect.

M. A. Morris [72] reports that fabric thickness gives the most accurate estimate of thermal insulation for single plies of fabric, but asserts that the volume of air per unit area provides improved accuracy of the estimate for multiple fabric layers. The additive thermal insulation values of smooth plies is demonstrated to be a more accurate estimate of thermal insulation than the additive resistance values of rough fabric plies. Multiple fabric layers appear to increase the thermal insulation of a garment assembly with the introduction of air barriers between them.

Stoll [92] explains that the net effect of radiant exposure on a fabric cross section depends on the spectral characteristics of the source and the optical properties of the material. Generally, more incident radiation is reflected by lighter color fabrics. When the heat that is transmitted through a fabric exceeds desirable levels, the amount of energy absorbed may be reduced by increasing the reflectivity of the outer fabric surface. Metallic or reflective films decrease radiant heat losses with their low emissivities. Emissivity is the ratio of the intensity of radiation emitted by a body to the corresponding intensity of the radiation from a block body [78]. The term refers to a quantity of heat lost per unit area, per unit time, for a unit temperature difference. Surface emissivity is one of the primary factors influencing thermal insulation when radiation is the dominant mechanism of heat transfer [54]. Low emissivity MLI fabrics are characteristically used in the TMG to minimize heat transfer to the interior of the space suit. However, Baxter and Cassie [9] indicate that the importance of emissivity rapidly diminishes when applied to other than the upper surface of a multi-ply fabric cross section. Furthermore, Benisek et al. [14] point out that although aluminized fabrics offer better protection against radiant heat than non-aluminized fabrics, they may provide for more conductive transfer through the fabrics. These concepts are discussed in greater detail in the following section.

Multilayer Insulation and Space

The principles of heat transfer for atmospheric and space environments are the same, although the relative significance of conduction, convection and radiation differ. All three modes of heat transfer apply to the thermal properties of fabrics tested in a gaseous environment. Gaseous conduction is the most significant factor in the presence of air [19]. However, radiative transfer generally becomes proportionately more significant in a vacuum. The absence of a fluid medium in space eliminates the convective and gas conductive modes of heat transfer in this context [39].

Multilayer insulation (MLI) provides thermal protection for the

Micrometeoroid Garment (TMG) in space. The low conductivity of the MLI used relies on the separation of adjacent metallized radiation shields, the removal of gas from the voids between them, and the correspondingly small contributions of solid and gas conduction [39]. The concept derives from the vacuum insulated glass Dewar flask, and applies to hot and cold temperatures [39].

Many studies describe the development of MLI insulation systems for use during extravehicular activity (EVA). Knesak and French establish the feasibility of the coverall concept for the TMG during the first space suit thermal test program [35]. Whisenhunt and Knesak present the first approximation of insulation for EVA using low density, porous insulation evacuated to space vacuum [82]. The concept of using multiple layers of reflective film layers with intervening spacers for space suit insulation is analyzed as early as 1958 by Billingham [15]. Multilayer insulation is used in all TMG configurations, although the number of layers and type of materials in the cross section varies [68]. Radiation shields include films which are metallized on one or two sides, perforated or unperforated, and reinforced or unreinforced. Spacer fabrics represent woven, nonwoven and other materials [68,35, 28,6].

An astronaut must achieve thermal balance between metabolic and radiant heat during EVA missions [79]. Energy balance with the surroundings is achieved by the radiation and absorption of incident energy [35]. External heat sources include solar radiation, planetary albedo and emitted radiation [73]. Bottomley and Roth [19] reference models of radiant input to the astronaut during EVA. Maximum temperatures represent the limiting condition for thermal protection, since cold temperatures are easily accommodated with any amount of insulation [83].

Heat flow in evacuated insulation includes simultaneous mechanisms of solid conduction through the material, and radiation across the voids and through the solid components [39]. Aerospace sources usually report the effective thermal conductivity for MLI, based on the one dimensional conductive heat transfer of Fourier's Law [24] (Equation 1). The equation does not govern the actual transport mechanism of thermal energy, and represents only the conductive form of heat transfer [24]. Certain researchers assert that thermal conductance is a more valid indication of MLI effectiveness for the TMG than conductivity [4,5,6,80,81,82]. The reciprocal of conductance is resistance. Both relate to a unit thickness of material instead of accounting for specimen thickness. Experimental measurements are usually obtained from flat plate calorimeter tests [24].

In theory, the heat flux passing through an uncompressed sample of MLI permits the calculation of thermal parameters. Heat flux of MLI is inversely related to the sample thickness and the number of uncompressed low emittance radiation shields, and is directly proportional to the emittance of the shield surfaces [19,73]. Low emittance radiation shields permit a greater degree of reflection of incident radiation [80]. However, experimentally obtained values of heat flux for MLI generally exceed predicted values [19]. Variables influencing MLI performance include boundary temperatures, compressive loads applied, the number of shields and perforations, and any gas present and its pressure [35]. Compression increases heat transfer and constitutes the major limitation of MLI. Other shortcomings include melting, embrittlement, flaking, reduced reflectivity, oxidation and reaction [39].

The relative contribution of radiation to total heat transfer varies by the degree of evacuation and the compression of MLI. The dominant mechanism of heat transfer in evacuated and uncompressed MLI is thermal radiation [39]. The use of highly reflective surfaces to attenuate thermal radiation in this context is well established [44]. MLI should be evacuated to less than 10^{-4} torr to be effective [80]. Radiative heat transfer is directly proportional to the emittance of the surfaces and inversely proportional to the number of radiation shields between the two temperature boundaries [39]. Analysis indicates that the radiation heat transfer contribution to thermal conductivity is a function of the cube of the temperature and inversely proportional to the scattering and absorption [39]. Cunnington and Tien [25] claim that more radiation shields per given thickness of MLI will decrease the fractional contribution of radiative heat transfer and increase the amount of solid conduction. This relates to the effects of applied surface pressure, which results in reduced insulation thickness.

The thermal performance of MLI is substantially reduced by imposed surface loads. Fried et al. [36] conclude that the effect of compression on MLI is suited to contact conductance analysis. MLI compression can be attributed to inadequate dimensional tolerances, differential expansion, or induced loads [39]. Film spacing is influenced by TMG design, construction and contact pressure in use [35].

Loads on the TMG in excess of 1.0 psi are unusual, although transient loads up to 15 psi are possible [4,72]. Direct conduction in TMG seams appears to be the dominant mode of heat transfer [30], and can be attributed to the compression caused by stitching. Stimpson and Jaworski examine the effects of stitching, joints and other features on aluminized MLI [90]. Arthur D. Little [6] reports that foam and matted fiber spacers are superior to net spacers under compressive loads. Both are considered forms of multiple resistance MLI [39].

The presence of gas in fibrous insulation or MLI cross sections greatly reduces insulation performance. Lightweight insulations typically contain 95% void space by volume [60]. Consequently, at one atmosphere, the radiation component of heat transfer becomes small in comparison to gas conduction, and heat conduction becomes the dominant mode of heat transfer [19]. Insulations that contain gas exhibit the conductivity of that gas as the lower limit of conductivity, regardless of the material [93]. Midwest Research Institute reports that MLI effectiveness at atmospheric pressures is one thousand times less than when tested under evacuated conditions [68].

A basic conclusion that emerges for optimum TMG insulation is the selection of a fabric cross section that exhibits minimum solar absorptance and maximum emittance, establishing a low absorptivity to emissivity ratio [79,101]. The outer layer of the space suit is the most critical to thermal transmission [83]. When the exposed surface is illuminated the amount of heat conducted through the insulation is small compared to the radiant energy absorbed and reemitted to space [101]. The fabric surface approaches an adiabatic equilibrium temperature associated with the absorptivity to emissivity ratio of the surface [83]. NASA reports an equilibrium temperature for the Ortho-fabric of approximately 100°C in use [99]. This is the temperature used for the lower plate of the thermal conductivity apparatus used in the current research. The need to interpret the experimental results presented comparitively is reemphasized on account of the differences between experimental and actual end use conditions.

Flocked Fabrics

Flocking is a process which refers to the upright attachment of short textile fibers to an adhesive coated substrate. Methods of application are mechanical, electrostatic or a combination of both. Mechanical methods usually provide for superior flock adhesion, while electrostatic techniques result in improved fiber alignment and greater flock density [43]. The electrostatic method uses a strong electric field to align, propel and attach flock fibers [43]. AC or DC current is used to charge the potentials. Flock is supplied upwards or downwards [47]. Successful flocking produces a velvet-like pile fabric whose character depends on fiber length, fiber fineness and density of packing [87]. Combination electrostatic and mechanical methods are the most successful [46].

Flock fiber is classified as random or precision cut. Random cut flock is generally derived from staple fiber and varies in length. Precision flock is cut from tow within close tolerances of a specified length [43]. Maximum usable flock lengths vary by fiber type and denier [2,43].

Natural and synthetic fibers are used in flocking although precision cut flock is limited to the latter. Nylon and polyester flock offer excellent abrasion resistance and durability [2]. Polyester offers improved ability to withstand environmental exposure [2].

Adhesive requirements for successful flocking include flexibility, durability, good aging properties and acceptable drape and hand [32]. Adhesive choice depends on the substrate material and the intended use. An improper adhesive may cause fabric deterioration with time [32].

Proper adhesive application penetrates the fabric without striking through it, with some remaining at the fabric surface to anchor the flock [32]. Sometimes a two coat process is used, with an adhesive basecoat to level the fabric surface and fill yarn interstices, and a second coat to secure flock fibers [32]. Adhesive application ranges from five to fifteen mils wet thickness [32,43]. Heavy fabrics or long flock length requires heavier adhesive applications [32,43].

Flocking involves many variables of which systematized knowledge is limited. Coldwell and Hersh [23] identify 31 variables in DC flocking. There are no national standards to evaluate the quality or performance of flocked goods [10]. The selection and control of machine, flock, adhesive and environmental variables is described by some as an art [32]. Temperature, humidity, voltage, and viscosity may influence flocked fabric properties [46]. Ultimately, the physical and mechanical performance of flocked materials depends on the adhesion of the fiber to the substrate, fiber toughness and particularly on flock density [87].

It is generally desirable to select the lower length flock for a given denier to achieve maximum flock density. Coldwell and Hersh report that fiber length has the greatest influence on flock density with the two factor interactions of the flock denier and length rating second. On the average, increasing fiber length by 25% decreases the number of fibers sifted and flocked by about 50%, based on hexagonal close packing or circular fibers [23]. Maximum packing levels achieved are less than 25%, although Semenov demonstrates that densities can theoretically be improved [87]. The flocks used in TMG insulation test specimens are nylon of varied lengths and deniers, as identified in the discussion section of this report.

CHAPTER III

EXPERIMENTAL APPARATUS AND PROCEDURES

The Compressometer

The Compressometer is a device which is used to measure fabric thickness under known pressures. A Frazier Compressometer, manufactured by Frazier Precision Instrument Company, Gaithersburg, Maryland, is used to measure the thickness of individual and multiple plies of fabric. The instrument is described in detail by Schiefer [85]. The Compressometer is used in combination with other equipment to measure thermal properties of fabrics, as described below.

Thermal Conductivity Apparatus

The thermal conductivity apparatus measures thermal transmission through individual fabrics and composite layups as a function of compression. The equipment includes the Compressometer, a special presser foot, and incorporates heat flux, temperature control and measurement devices. The set up is shown schematically in Figure 2.

A special presser foot is designed to measure temperature and heat flux. A four inch by four inch aluminum presser foot of comparable weight replaces the standard one inch diameter foot. The lower surface of the foot is machined to flush mount a thermocouple (T_2) and a thermopile near the center of the plate. The area is illustrated in Figure 3.

Heat is supplied to the system by a hot plate which is controlled to maintain constant temperature. A temperature probe in the lower

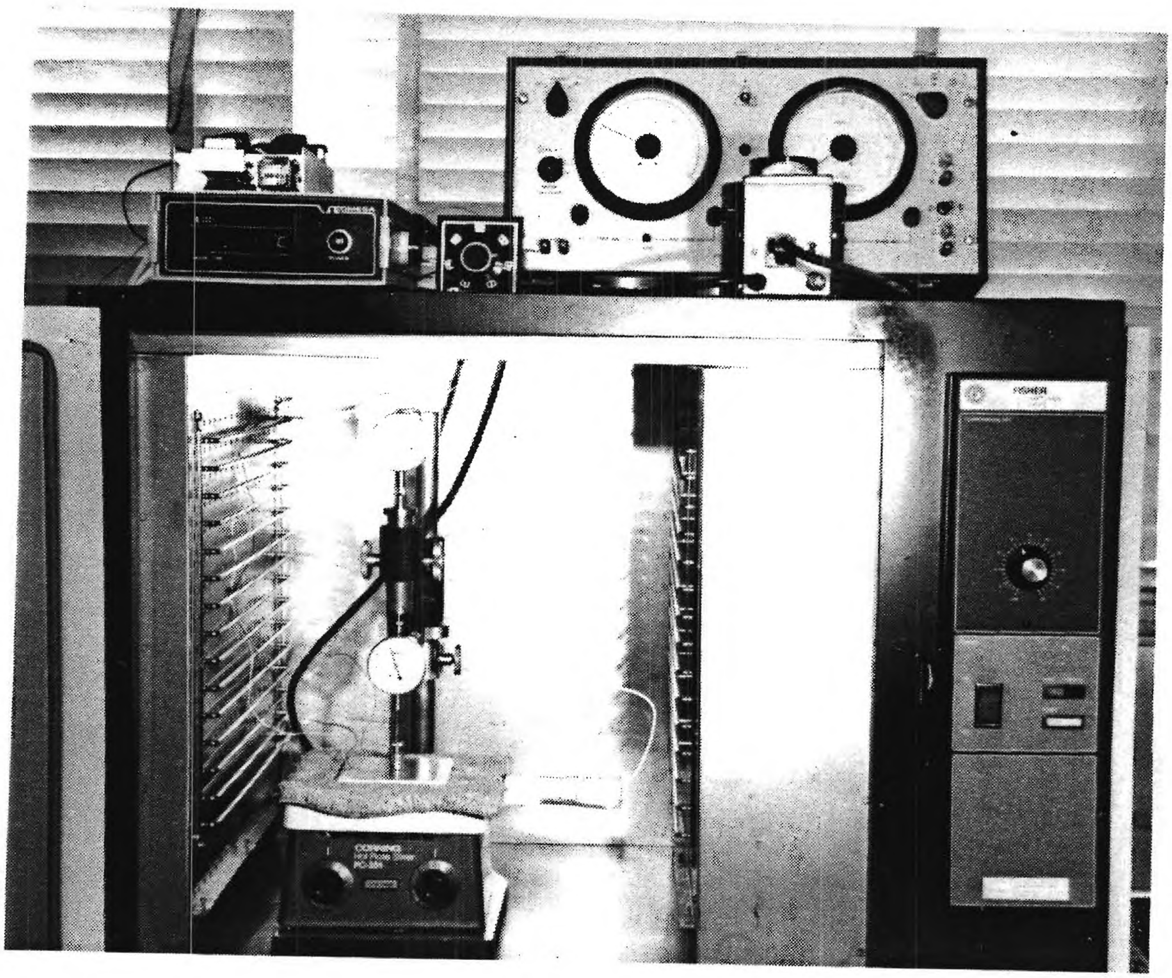

Figure 1. Experimental Apparatus.

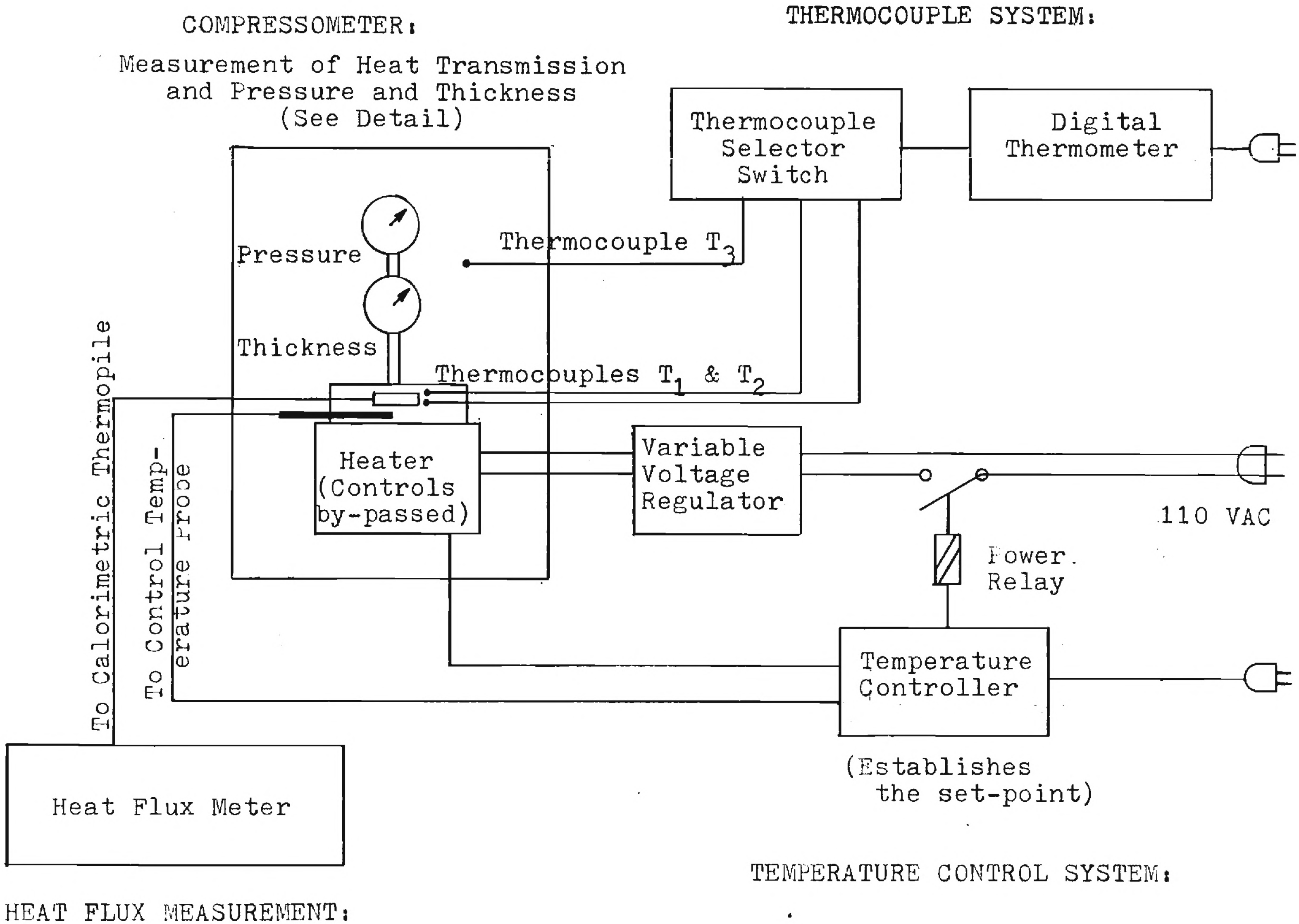

Figure 2. Schematic of Thermal Conductivity Apparatus.

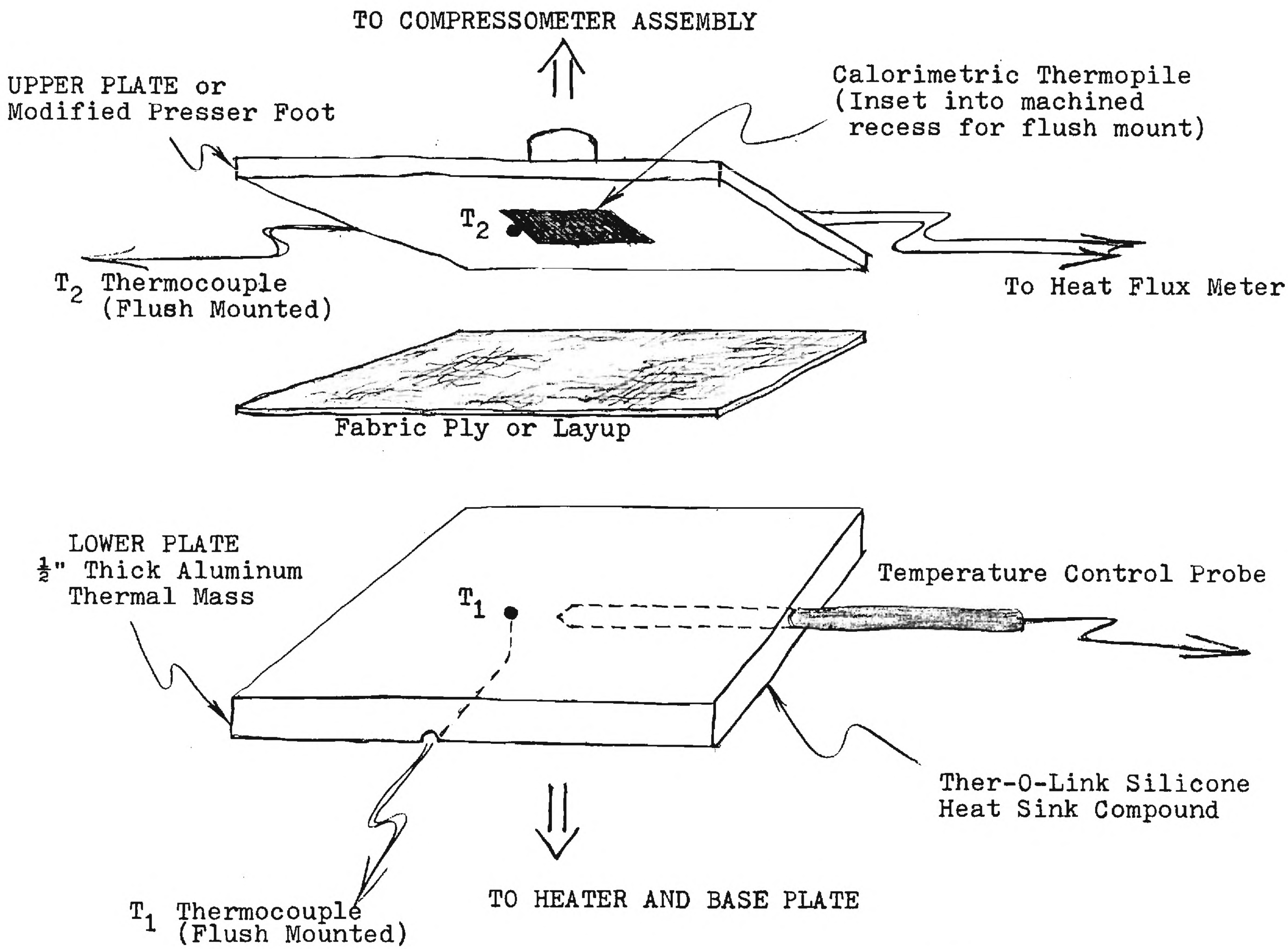

Figure 3. Illustration of Thermal Conductivity Apparatus, Detail.

plate senses temperature on the underside of the specimen. A temperature controller switches the heater on and off to sustain a lower plate temperature of 100° ± 1°C. A variable voltage regulator minimizes control gain and associated temperature overshoot in the control loop.

Temperature is measured at three locations in the assembly. Thermocouples T_1 and T_2 measure temperature on either side of the specimen and establish the temperature gradient across fabric boundaries. T_1 is located in the aluminum plate which rests below the specimen. T_2 is flush mounted to the underside of the special pressure foot suspended above the specimen. A third thermocouple monitors ambient temperature within the test enclosure. All are teflon insulated, AWG 30, chromel-alumel thermocouples. A selector switch provides for sequential temperature readings from the thermocouples on a digital thermometer.

A calorimetic thermopile is incorporated in the presser foot to measure heat flux through the fabric specimen. A thermopile contains a group of differential thermocouples connected in series. The device generates an amplified signal that is linear and proportional to the applied heating rate at any given instant. A Hy-Cal LO-6 thermopile, manufactured by Hy-Cal Engineering, Sante Fe Springs, CA, is used with a Hy-Cal $\dot{Q}$ meter to convert the millivolt output to a direct analog reading of heat flux.

Several other features of the thermal conductivity apparatus facilitate measurement procedures. A longer shaft replaces the original vertical rod of the Compressometer to accommodate the hot plate used for thermal tests. The entire Compressometer assembly is housed in an oven which serves as a protective enclosure. A silicone heat sink compound bridges gaps between the lower plate and the heater surface and between the presser foot and the thermopile. A form fitting slab of carpet surrounds the test specimen to guard against lateral heat transfer and to minimize convective influences.

Thickness vs. Pressure Measurements

The Compressometer is calibrated using a balance and counterbalancing loads as described by Schiefer [85], for standard and replacement presser feet. The calibration curve for the standard foot matches the values provided by the manufacturer.

The thickness of individual fabrics are obtained in accordance with ASTM test D1777-64. Fabrics tested are listed in Table 11. A one inch diameter foot exerts successively increasing pressures on four inch by four inch specimens. Thickness is measured five seconds after loading, and represents the average of three readings. Correction factors are included to compensate for small but reproducible deflections. Pressures applied with the standard presser foot are 0.100, 0.200, 0.350, 0.500, 0.750, 1.000, 1.500, 2.000, 2.500, and 3.000 psi. Thickness measurements are reported in Appendix B.

An initial reading of nominal thickness is reported. This value is associated with the minimum spring elongation perceptible by the Compressometer, as evidenced on the upper dial. Corresponding pressures are in the vicinity of 0.001 psi. Correction factors are not applied for nominal thickness measurements. Compressometer dials are tapped as required during use to minimize frictional influences on readings.. Thickness readings with correction factors added are verified to within 0.001 inch using flat thickness gauges to measure plate separation.

Thermal Transmission Measurements

Selected fabric plies and composite layups are tested for thermal transmission over a range of pressures and compared to values obtained for the TMG cross section (layup #12) measured under the same conditions. Layups are identified schematically in Figure 8. Fabric thickness, boundary temperatures and heat flux are used to calculate values of thermal conductivity, thermal conductance and thermal resistance. All measurements are obtained at thermal equilibrium, defined in this context as a steady temperature gradient (T_1-T_2) across the fabric specimen. Temperatures were converted from Centigrade to Fahrenheit for calculation in English units.

Careful adjustment is required to reference the Compressometer presser foot to the lower plate and to ensure accurate thickness measurements. The foot must remain plane and parallel to the surface below it. Proper orientation is facilitated by placing the foot on the lower plate surface and lowering the spindle to the foot for attachment. A knurled nut engages the spindle in the threaded flange of the presser foot. The bezel of the lower indicator is adjusted to zero thickness when the foot initiates contact with the plate. The onset of pressure should coincide with the point of contact between these surfaces as the foot is lowered.

To obtain thermal measurements a four inch by four inch specimen is placed on the lower plate, which rests in turn, on the temperature controlled hot plate. The specimen is oriented with outward facing side against the lower plate. The Compressometer presser foot is lowered to apply a known pressure established by prior calibration. The oven door is closed and the system is permitted to come to equilibrium. Heat flux readings are monitored and averaged over periods of approximately five minutes, or a minimum of one on/off cycle of the hot plate. Thickness values are noted upon opening the oven at the end of each test pressure. The time required to reach steady state conditions is within one hour of pressure adjustment. Conditions are monitored at apparent equilibrium for 15 minutes before taking final readings at each pressure. Previously established correction factors to account for instrument deflection are included in reported values. These are larger than those measured in the absence of the thermal apparatus, but are equally reproducible. Thicknesses are verified to within 0.001 inch using flat thickness gauges.

The thermal data is obtained in several stages to identify those alternative TMG cross sections which may offer improved physical properties. First, individual fabrics within each group are compared at a single pressure. Thermal, mechanical, and aesthetic properties are used to select fabrics from PTFE, substrate fabric, flocked substrate, flocked blanket, and terry cloth groups. From these, composite cross sections are selected for additional thermal tests, performed at nominal thickness and under 0.200 psi of pressure. Results are reported in Appendix C. Layups are identified schematically in Figure 8. Finally, thermal, functional and aesthetic criteria aid in identifying two of the most promising layups for additional thermal tests over a range of pressures. These are identified as layups #4 and #10. Data is compared to the seven layer TMG cross section (layup #12) tested under identical conditions, as reported in the Results section of this report. A repeated test demonstrates the reproducibility of the results, as obtained for the TMG, and included in Appendix D.

CHAPTER IV

EXPERIMENTAL RESULTS

Experimental data fall under several broad categories. Comparative thermal data for fabric plies and composite layups are included in this section. Also included here are thermal results for selected layups #4 and #10 and the seven layer TMG cross section (layup #12) as a function of pressure. Measurements of fabric thickness are reported over a range of pressures in Appendix B. Thermal data for eleven original layups is included in Appendix C. Comparable data obtained for the MLI cross section during two separate tests is available in Appendix D. The TMG data demonstrates good reproducibility of results. Physical properties of the fabrics used are included in Appendix A.

Table 1. Thermal Data - PTFE Fabrics.

PTFE Fabric	$\Delta T = (T_1 - T_2)$ (°F)	Conductance $\left(\frac{Flux}{°F}\right)$	Conductivity $\left(\frac{Flux-Ft}{°F}\right)$	R Value $\left(\frac{Hr-Ft^2-°F}{BTU}\right)$
T-187-30	3.6	26.25	0.01	0.04
T-162-42	5.4	18.61	0.02	0.05
T-388-43	5.4	20.28	0.02	0.05
604	5.4	18.70	0.02	0.05
Ortho-Fabric	12.6	11.39	0.02	0.09

*NOTE: All measurements taken at 0.2 psi applied surface pressure.

Table 2. Thermal Data - Substrate Fabrics.

Substrate Fabric	$\Delta T = (T_1 - T_2)$ (°F)	Conductance $\left(\frac{Flux}{°F}\right)$	Conductivity $\left(\frac{Flux\text{-}Ft}{°F}\right)$	R Value $\left(\frac{Hr\text{-}Ft^2\text{-}°F}{BTU}\right)$
15300	9.0	15.39	0.02	0.07
15004	5.4	19.63	0.01	0.05
15138	5.4	20.28	0.02	0.05
15364	3.6	25.42	0.01	0.04
15530	10.8	12.50	0.02	0.08
15782	7.2	15.56	0.01	0.06

*NOTE: All measurements taken at 0.2 psi pressure.

Table 3. Thermal Data - Flocked Substrates.

			Flock (-1)	Flock (-2)	Flock (-3)	Flock (-4)	Flock (-5)
Substrate 15364	ΔT	(°F)	18.00	21.60	36.00	25.20	18.00
	C	$\left(\frac{Flux}{°F}\right)$	8.08	7.06	3.75	5.40	8.36
	k	$\left(\frac{Flux\text{-}Ft}{°F}\right)$	0.02	0.03	0.03	0.02	0.02
	R	$\left(\frac{Hr\text{-}Ft^2\text{-}°F}{BTU}\right)$	0.12	0.14	0.27	0.19	0.12
Substrate 15782	ΔT	(°F)	19.80	19.80	30.60	23.40	16.20
	C	$\left(\frac{Flux}{°F}\right)$	7.07	6.92	4.46	5.53	9.10
	k	$\left(\frac{Flux\text{-}Ft}{°F}\right)$	0.03	0.03	0.03	0.02	0.03
	R	$\left(\frac{Hr\text{-}Ft^2\text{-}°F}{BTU}\right)$	0.14	0.14	0.22	0.18	0.11

*NOTE: All measurements taken at 0.2 psi applied surface pressure.

Table 4. Thermal Data - Terry Cloths.

			6625 (Lt. Wt.)	6883 (Med. Wt.)	6995 (Hvy. Wt.)	1000 (Knit)
Unsheared	ΔT	(°F)	37.8	43.2	45.0	45.0
	C	$\frac{\text{Flux}}{°\text{F}}$	3.64	2.99	2.69	2.90
	k	$\frac{\text{Flux-Ft}}{°\text{F}}$	0.03	0.03	0.03	0.03
	R	$\frac{\text{Hr-Ft}^2\text{-}°\text{F}}{°\text{F}}$	0.27	0.33	0.37	0.34
Sheared 1 Side	ΔT	(°F)	37.8	43.2	41.4	41.4
	C	$\frac{\text{Flux}}{°\text{F}}$	3.73	3.03	3.12	3.29
	k	$\frac{\text{Flux-Ft}}{°\text{F}}$	0.03	0.03	0.03	0.03
	R	$\frac{\text{Hr-Ft}^2\text{-}°\text{F}}{°\text{F}}$	0.27	0.33	0.32	0.30
Sheared 2 Sides	ΔT	(°F)	34.2	37.8	37.8	39.6
	C	$\frac{\text{Flux}}{°\text{F}}$	4.01	3.58	3.68	3.31
	k	$\frac{\text{Flux-Ft}}{°\text{F}}$	0.03	0.03	0.03	0.03
	R	$\frac{\text{Hr-Ft}^2\text{-}°\text{F}}{°\text{F}}$	0.25	0.28	0.27	0.30

*NOTE: All measurements taken at 0.02 psi applied surface pressure.

Table 5. R Values - Composite Layups, Group 1

Layup ID	Fabric Layers Outer - Middle - Inner	Pressure (psi)	R Value $\left(\frac{Hr\text{-}Ft^2\text{-}°F}{BTU}\right)$	R Value Relative to TMG
#1	Ortho Fabric - (None) - Short Flock	NOM	0.25	50%
		0.2	0.16	84%
#2	Ortho Fabric - (None) - Long Flock	NOM	0.33	66%
		0.2	0.26	137%
#3	604 - (None) - Short Flock	NOM	0.20	40%
		0.2	0.13	68%
#4	604 - (None) - Long Flock	NOM	0.32	64%
		0.2	0.26	137%

Table 6. R Values - Composite Layups, Group 2

Layup ID	Fabric Layers Outer - Middle - Inner	Pressure (psi)	R Value $\left(\frac{Hr\text{-}Ft^2\text{-}°F}{°F}\right)$	R Value Relative to TMG
#5	604 - 1 alum. mylar - Short Flock	NOM	0.22	44%
		0.2	0.15	79%
#6	604 - 1 alum. mylar - Long Flock	NOM	0.34	68%
		0.2	0.26	137%
#7	604 - Short Flock - Short Flock	NOM	0.28	56%
		0.2	0.18	95%
#8	604 - Long Flock - Long Flock	NOM	0.37	74%
		0.2	0.28	147%

Table 7. R Values - Composite Layups, Group 3

Layup ID	Fabric Layers Outer - Middle - Inner	Pressure (psi)	R Value $\left(\frac{Hr\text{-}Ft^2\text{-}^\circ F}{BTU}\right)$	R Value Relative to TMG
#9	604 - Terry 6995, US - 15364	NOM	0.60	120%
		0.2	0.41	216%
#10	604 - Double Flocked Foam - 15364	NOM	0.79	158%
		0.2	0.60	316%
#11	604 - Double Flocked Foam - TMG Liner	NOM	0.78	156%
		0.2	0.62	326%

Table 8. R Value vs. Pressure - TMG Cross Section.

Applied Pressure (psi)	R Value: $\left(\frac{Hr\text{-}Ft^2\text{-}°F}{BTU}\right)$		
	Test #1	Test #2	Average
NOM	0.42	0.57	0.50
0.050	0.25	0.25	0.25
0.100	0.20	0.22	0.21
0.150	0.20	0.20	0.20
0.200	0.18	0.19	0.19
0.250	0.17	0.19	0.18

Table 9. R Value vs. Pressure - Layup #4.

Applied Pressure (psi)	R Value $\left(\frac{\text{Hr-Ft}^2\text{-°F}}{\text{BTU}}\right)$	R Value Relative to TMG
NOM	0.30	60%
0.050	0.26	104%
0.100	0.25	119%
0.150	0.25	125%
0.200	0.23	121%
0.250	0.23	128%

Table 10. R Value vs. Pressure - Layup #10.

Applied Pressure (psi)	R Value $\left(\frac{Hr\text{-}Ft^2\text{-}°F}{BTU}\right)$	R Value Relative to TMG
NOM	0.81	162%
0.050	0.74	296%
0.100	0.68	324%
0.150	0.65	325%
0.200	0.67	353%
0.250	0.65	361%

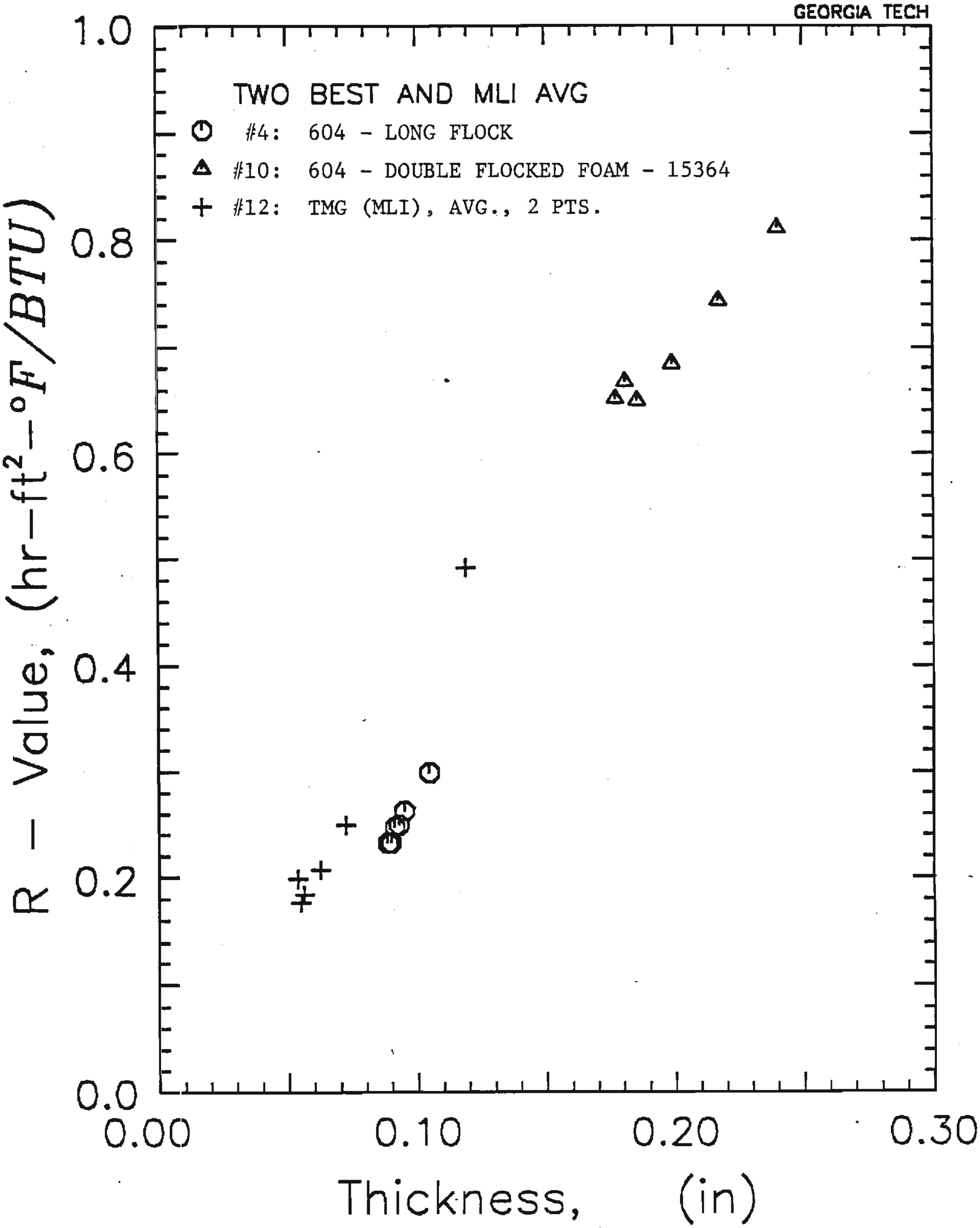

Figure 4. R Value vs. Thickness - Layups #4, #10 and TMG.

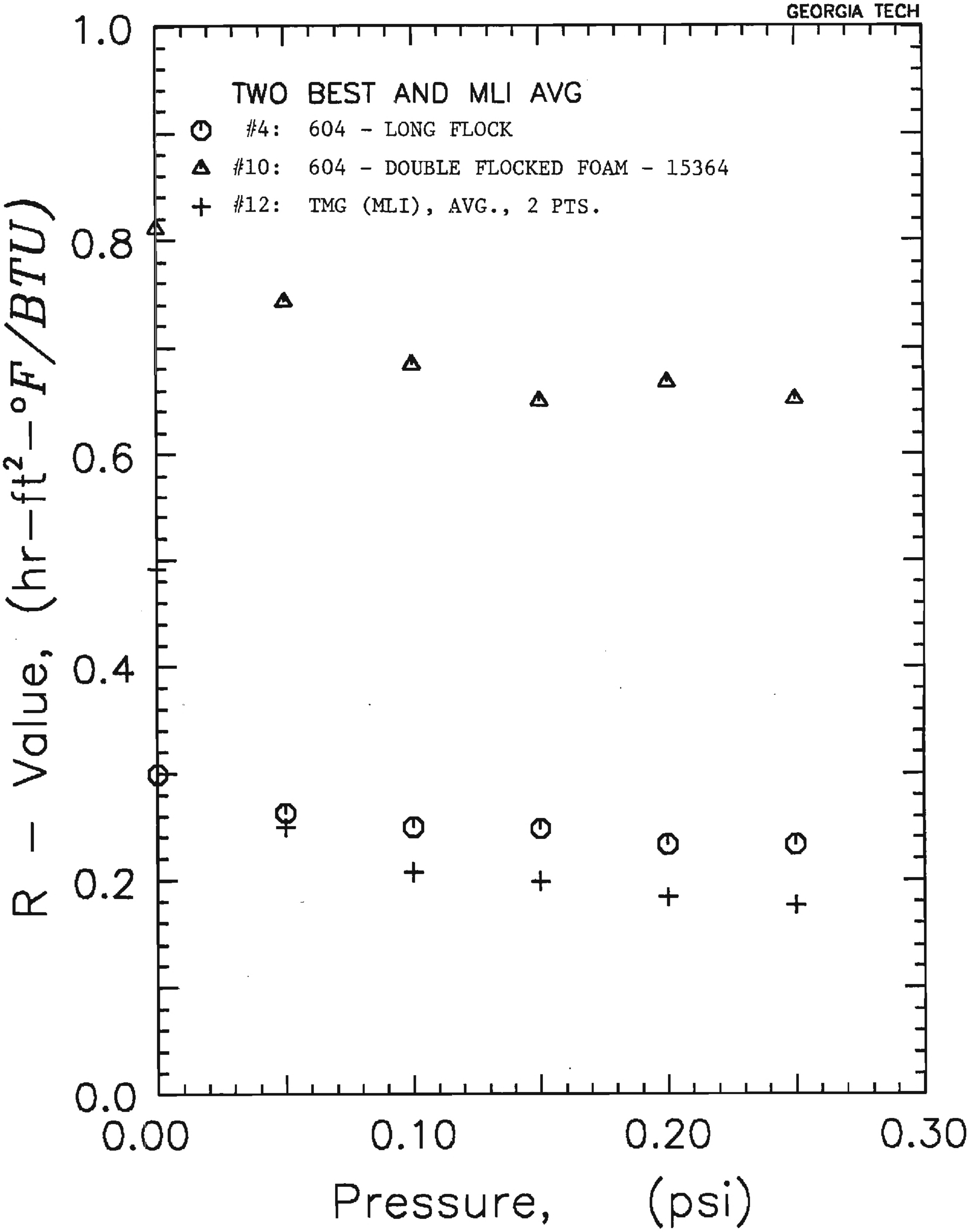

Figure 5. R Value vs. Pressure - Layups #4, #10 and TMG.

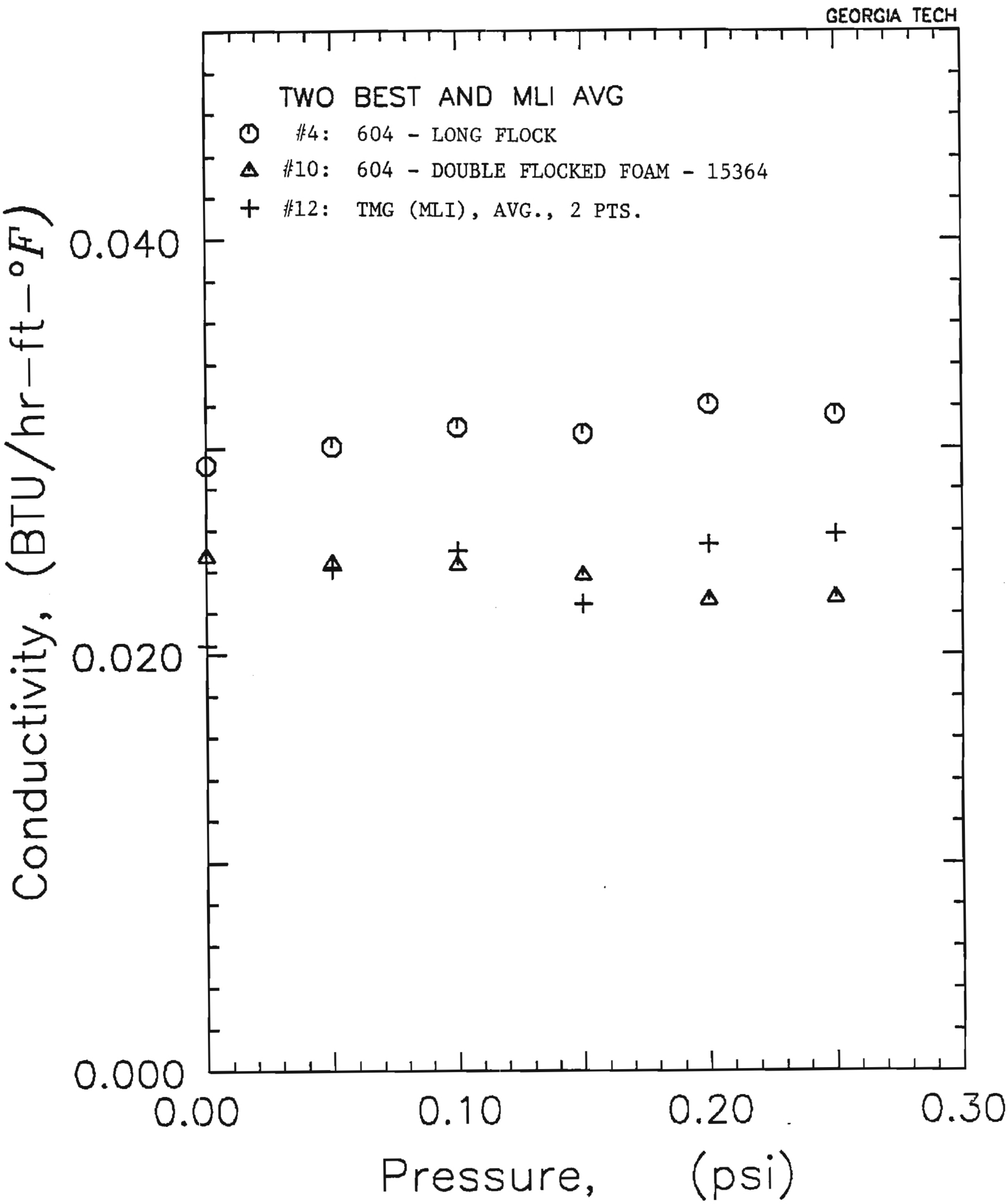

Figure 6. Conductivity vs. Pressure - Layups #4, #10 and TMG.

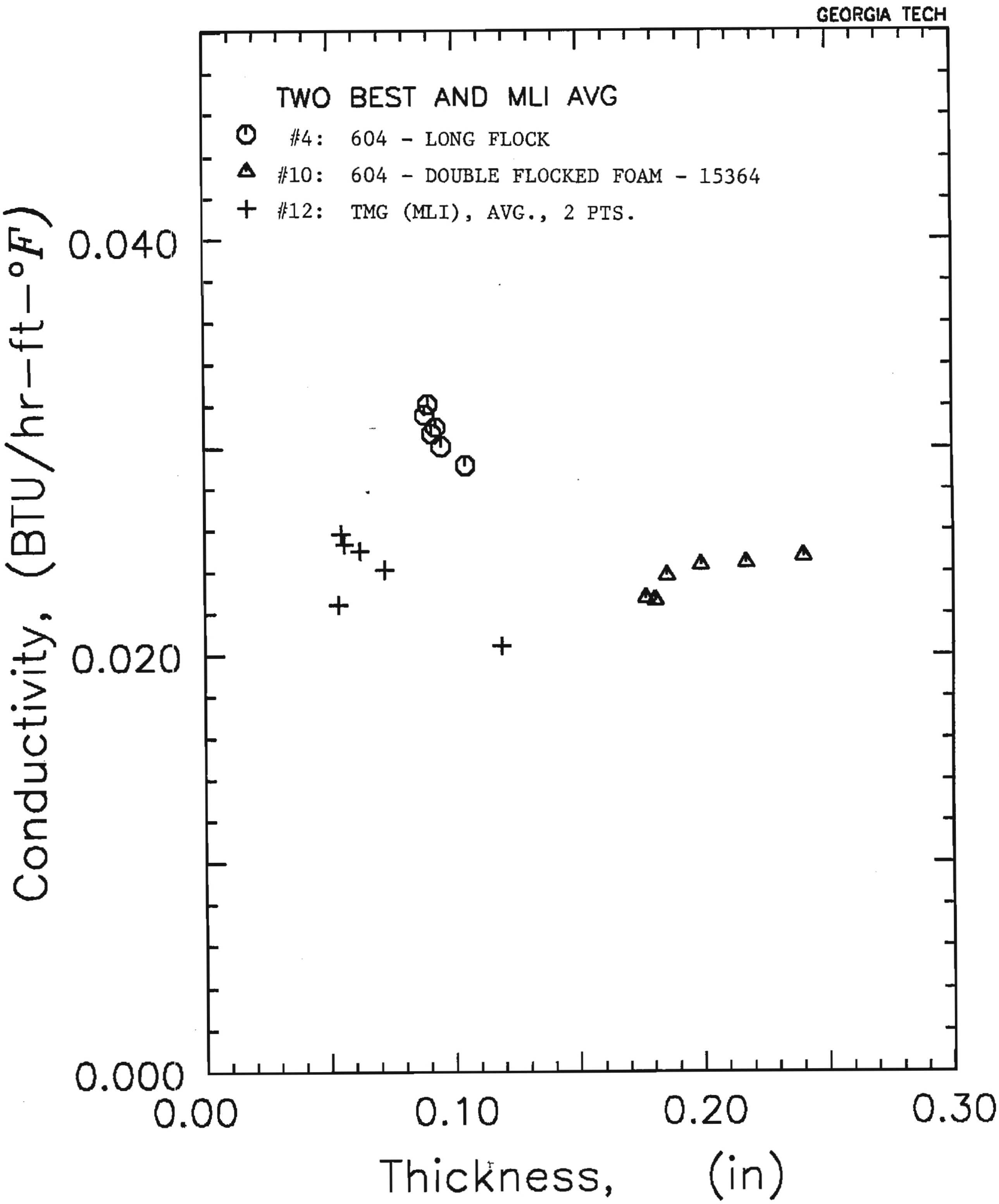

Figure 7. Conductivity vs. Thickness - Layups #4, #10 and TMG.

CHAPTER V

DISCUSSION

This investigation aims to identify a fabric cross section for improved Thermal Micrometeoroid Garment (TMG) insulation under compressive loads. Multilayer insulation (MLI) is effective under ideal conditions in space, but compressive loads substantially reduce its protective value in the TMG. A fabric layup that maintains its thickness under pressure or retains its thermal properties under compression offers an alternative TMG approach. Pile fabrics possess inherent thickness and other properties which may provide improved protection in use. Fabrics tested include polytetrafluorethylene (PTFE) fabrics, substrate fabrics, flocked substrates, flocked blankets, and terry cloth fabrics (Table 11). A discussion of the selection of specimens from each group is followed by an examination of the composite cross sections which combine them. Flocked and terry pile fabrics serve as monolayer or multilayer insulation plies within the alternative TMG layups. Twelve cross sections are thermally tested, including the Shuttle seven ply TMG, which consists of five MLI films between inner and outer garment layers (Figure 8).

Fabric Plies

Five PTFE fabrics of varied weight and construction are tested for the outermost layer of the TMG, including the Ortho-fabric used in the current Shuttle TMG. Of these, the Ortho-fabric and the lighter

Table 11. Fabric Groups Tested.

Fabric Group	Specimens Tested
PTFE Fabrics	Ortho-Fabric and four other PTFE (Gore-Tex or Teflon) fabrics of varied weight and construction.
Substrate Fabrics	Six Dacron polyesters of varied weight and construction.
Flocked Substrates	Six substrate fabrics (above) with five types of flock. Flock varies by fiber type, length and denier.
Flocked Blankets	Ten total specimens from two sources. Nine double flocked foams and one single flocked nonwoven.
Terry Cloths	Twelve total specimens of four types and three pile configurations including unsheared and sheared one or two side varieties.

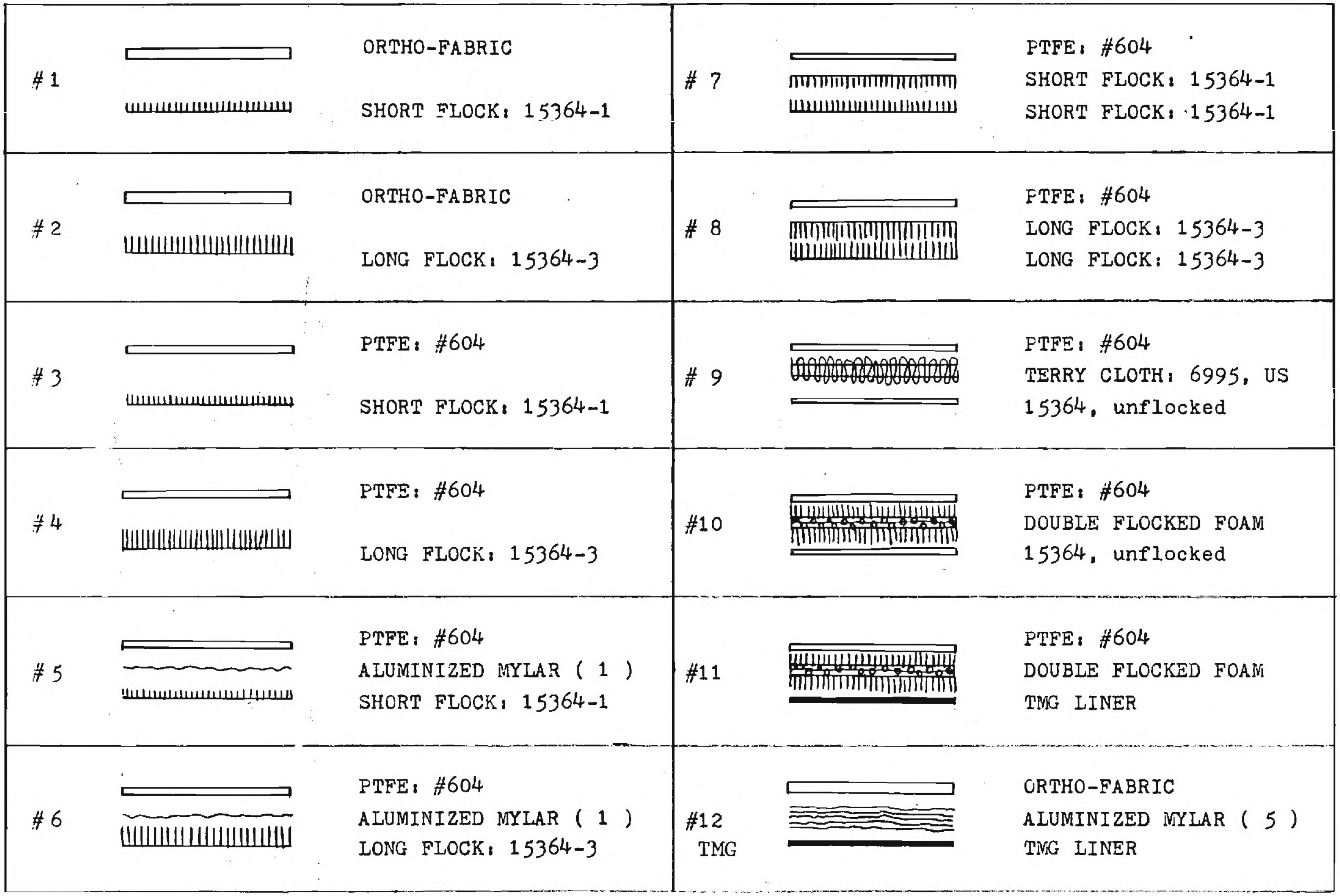

Figure 8. Schematic of Composite Layups.

weight Gore-Tex style 604 are selected for inclusion in the experimental layups.

There are several reasons to retain the Ortho-fabric on the outside of the TMG. Firstly, the reported 100°C adiabatic equilibrium temperature of the existing TMG exterior is used to establish the lower plate temperature in this study. In addition, the Ortho-fabric performs adequately in actual use, while the adequacy of untested fabrics is somewhat speculative. Furthermore, the net effect of radiant exposure of an insulation system depends largely on the optical properties of the exterior, which are not tested directly or under representative conditions. However, the present fabric construction is complex, and weighs 14.7 oz/yd^2, warranting consideration of a replacement. Style 604 Gore-Tex compares most favorably with the Ortho-fabric, with respect to tensile strength, lighter weight, improved flexibility and comparable levels of air permeability, which bears some relation to the spectral properties of the fabric (Table A1). Furthermore, the satin weave construction probably exhibits greater reflectance than the plain woven Gore-Tex exterior of the Ortho-fabric. Both fabrics are used in composite cross sections for comparison with the current TMG design (Figure 8).

Six Dacron polyester fabrics are considered for the inner layer of the TMG and as a substrate for flocking (Table A2). These include satin, twill and plain weave fabrics weighing between two and nine oz/yd^2. The two heaviest fabrics are too stiff after flocking. The two lightest fabrics tend to permit excessive adhesive penetration, although they produce acceptable flocked fabrics. The remaining substrate fabrics, numbers 15364 and 15782, produce the most satisfactory flocked fabrics. Thermal data between both sample sets are similar (Table 3). Fabric 15364 is selected instead of 15782 because its smooth fabric surface permits more uniform adhesive application and homogeneous flock deposition. Furthermore, its slippery hand is desirable for the inside surface of the TMG.

Each polyester fabric serves as a substrate for five types of flock which vary by length, denier and fiber type, as identified below:

-1: White nylon flock, 0.030", 3 denier

-2: White nylon flock, 0.045", 6 denier

-3: White nylon flock, 0.080", 20 denier

-4: White nylon flock, 0.180", 20 denier

-5: White polyester flock, 0.030", 3 denier

Only twenty eight of the thirty possible combinations of substrate and flock are available because the two lightest fabrics are not suited to the heavier adhesive application required for the longest flock. Flock codes are appended to fabric numbers to uniquely identify the flocked substrates (Table A3). The addition of flock lowers fabric bulk density considerably from that of the substrate fabrics alone (Tables B3 to B9). Resistance values of flocked substrates are greater than those of the substrates alone (Tables 2 and 3), although some increase in conductivity values is witnessed. This could possibly be related to the more conductive orientation of fibrous material aligned parallel to the direction of heat flux. Fabrics 15364-1 and 15364-3 are chosen from among the flocked specimens to represent long and short flocks (also referred to as high and low flocks), respectively. Observations regarding the full set of flocked specimens are noted briefly.

Comparison between substrates flocked with -1 and -5 fibers permit some significant observations. These fabrics contain nylon and polyester flock, respectively, precision cut to the same length. The higher density of polyester than nylon, and the smaller diameter of polyester flock fibers than nylon fibers of the same denier, contribute to the polyester flocked substrates consistently having the highest bulk density (Tables B4 to B9). The smaller diameter of the polyester flock permits closer packing of the pile. The nylon flock fabrics tend to resist compression better than the comparable polyester flocked fabrics under nominal loading. However, the polyester pile fabrics perform better at greater loads. The higher bending modulus of the larger diameter nylon fibers may contribute to the initial compression response. The improved ability of the polyester flocked substrate to retain fabric thickness under increased loads may be associated with greater flock density and greater load sharing among more fibers. Among the nylon flocks, the shortest flock with the smallest diameter produces the highest density flocked fabrics (Tables B4 to B9). Progressively longer flocks exhibit reduced flocked fabric densities when uncompressed, based on flocked substrate weights, assuming comparable substrate and adhesive weights. Increasing loads tend to compress the lower density piles more readily. However, the lower density and less upright alignment of the longest flock flattens easily under compressive loads, and contributes to greatly increased bulk densities of these fabrics under high compressive loads. In some instances, changes in fabric thickness result from fiber slippage rather than gradual fiber deformation, manifested as abrupt changes in thickness (Figures B6 to B9). Thermal data for the 15364-1 and the 15364-5 are very similar (Table 3). There is no clear preference for the short flock to be included in insulation layups. The 15364-1 is selected for purposes of comparison with the other flocks, which are also nylon.

Of the three remaining nylon flocks, the intermediate length, -3, is selected for further consideration. It produces the thickest fabrics at all pressures, which exhibit the highest R values, the lowest conductance figures and the greatest temperature drop across fabric boundaries, when tested under 0.200 psi pressure (Table 3). The 15364-3 is superior to the 15782-3, and is selected for testing in composite layups. Long flock or high flock descriptors refer to this specimen.

Twelve varieties of terry cloth are investigated, representing lightweight, medium weight, heavyweight and knitted specimens in unsheared, sheared one side and sheared two side pile configurations (Table 4). The group exhibits certain predictable trends in thermal data. As the fabrics are sheared they lose thickness and gain density when uncompressed, a consequence of improved surface uniformity. As thickness or weight decreases the temperature gradient across the specimen and the thermal resistance decrease. The more uniform and upright cut pile fibers seem to resist compression slightly better than uncut terry cloth loops (Tables B12 to B15). However, the unsheared heavyweight terry cloth specimen is selected for additional thermal tests based on the highest R value measured under loading (Table 4).

The fabric is judged too bulky for the TMG upon further consideration.

Ten industry provided flocked blankets are examined in this investigation. With one exception, these are actually scrim reinforced foams flocked on both sides, and sold commercially as blankets. Seven specimens are from Fieldcrest Mills and three are from W. P. Pepperell. All contain nylon flock secured with an acrylic adhesive. Blankets are identified by color for convenience, although identified by the same specifications. Varied compressive response is presumably due to variations in flocking conditions, to which the process is extremely sensitive. The Fieldcrest seafoam colored specimen is selected initially because it retains its thickness best and exhibits the lowest density at highest pressures (Tables/Figures B10 and B11). However, an additional sample obtained later exhibits somewhat different responses. Ultimately, an ivory colored blanket from W. P. Pepperell is used to fabricate a mock-up TMG segment. This particular fabric is not included among samples tested.

Composite Layups

Eleven experimental TMG layups are evaluated, which represent combinations or layups of the plies selected previously. Cross sections contain two or three fabric layers, and are tested thermally at nominal and 0.200 psi pressures. Refer to Figure 8 for a schematic of the fabric combinations tested. These are reported in three groups of cross sections in Appendix C, and summarized by Tables 5, 6 and 7. Four double layer assemblies include flocked substrates with Orthofabric or Gore-Tex style 604 outer layers (layups #1, 2, 3, and 4).

Two three ply combinations represent the addition of one aluminized film layer (layups #5 and 6), the use of two flocked plies (layups #7 and 8), and the use of terry cloth and flocked blanket materials with liner fabrics (layups #9, 10 and 11). Of these layups, seven exceed the thermal insulation of the Shuttle TMG cross section tested at 0.200 psi pressure under atmospheric conditions (Tables 5, 6 and 7). These are layups #2, 4, 6, 8, 9, 10 and 11. Layups #10 and 11 exceed TMG insulation performance at nominal load, although all are within limited range of it. Of these, layups #8 and 9 are eliminated for exceeding the 28.1 oz/yd^2 weight of the Shuttle TMG at 28.6 and 28.2 oz/yd^2, respectively. Of the remaining layups, #4 is selected over layup #2 for comparable thermal performance at a lower weight. Layup #6, which duplicates layup #5 with one film layer added, shows only marginally better thermal resistance for its increased weight and cost of fabrication. All fabric weights are available in Appendix A.

Consequently, layups #4 and #10 are identified as the most promising, and are subjected to thermal testing as a function of loading (Tables C4 and C5). These are tested sequentially under pressures increasing to 0.250 psi. The TMG exhibits resistance values intermediate between layups #4 and #10 when uncompressed. Both alternatives perform better than the TMG under compressive loads. Results are given in Tables 8-10 and Figures 4-7. Layup #10 shows a 162%-361% improvement over TMG thermal resistance within the range of pressures specified. The linear relationship between specimen thickness and thermal resistance is graphically evident in Figure 4. Figure 5 demonstrates reduced thermal resistance as a function of increasing pressure and associated compression. The highest protection is witnessed in layup #10 among the three compared as a function of pressure. Figure 6 shows that the TMG and layup #4 become more conductive as compressed to smaller thicknesses. Layup #10 appears to improve slightly as compressed. Layup #10 exhibits 158% and 316% of the thermal resistance values for the TMG measured at nominal and 0.200 psi pressures, respectively. Subsequent tests on the same cross sections measure 162% and 361% of the resistance values for the TMG, denoting reproducibility of data within acceptable limits. Repeatability data is provided in Appendix D.

The feasibility of TMG fabrication with cross section #10 is demonstrated by construction of a reduced scale mock-up TMG section. Insulation pieces are cut and joined using a zig-zag stitch with wrong sides of fabric together. No edge lock is required before cutting the double flocked foam fabric. Sewn attachment of the garment layers is performed by machine with a minimum of bulk, more easily than the present MLI TMG cross section. Reduction of the scrim interstices within the foam may improve tensile strength and reduce tear propagation. Inner and outer TMG layers, referred to as the liner and shell by NASA are constructed from Gore-Tex 604 and polyester 15364 fabrics, respectively, in the same manner as Shuttle TMG components. It must be established if the foam monolayer insulation is able to protect against micrometeoroids as presently accomplished by a neoprene coated TMG liner.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The results of these experiments demonstrate improved thermal insulation of selected fabric layups in comparison to the TMG MLI cross section tested under identical atmospheric conditions. The improvement in thermal protection is more pronounced under higher compressive loads. Conclusions regarding the expected performance of alternative insulation systems for the TMG must await further testing in a space representative environment.

Two cross sections are selected from eleven composite layups considered for thermal testing as a function of pressure. The first layup has two plies, including a Gore-Tex outer layer and a polyester fabric flocked with 0.080" long, 20 denier nylon flock. The second layup includes three plies, containing a Gore-Tex outer layer, a scrim reinforced, double flocked foam insulation layer, and a lightweight polyester liner. The second cross section provides better thermal insulation.

The R values of both alternative cross sections are higher than the TMG at all comparable pressures beyond nominal loads. The divergence between comparative values increases as pressures increase. Thermal resistance values for the alternative layups range from 60% to 128% and from 162% to 361% of the TMG values over the range of surface pressures applied.

The feasibility of TMG fabrication using the superior cross section is demonstrated by construction of a reduced scale mock-up. Assembly is accomplished with greater ease than the MLI TMG, and aesthetic characteristics are improved. Additional testing under evacuated conditions is recommended.

APPENDIX A

PHYSICAL PROPERTIES

Table A1. Physical Properties - PTFE Fabrics.

FABRIC ID - CONSTRUCTION (WEAVE - COUNT)	WEIGHT (OZ/SQ YD)	NOMINAL THICKNESS (IN)	AIR PERMEABILITY (CFM)	TENSILE ----(LB)---- WARP	FILLING	ELONGATION ----(%)---- WARP	FILLING
T-187-30 TEFLON (PLAIN - 86 X 82)	4.50	.0053	29.4	78.	66.	50.%	47.%
T-162-42 TEFLON (PLAIN - 79 X 65)	9.92	.0097	3.2	173.	156.	74.%	58.%
T-388-43 GORETEX (2/2 TWILL - 72 X 70)	10.14	.0110	158.0	305.	287.	36.%	36.%
604 GORETEX (4H SATIN - 93 X 66)	8.61	.0123	38.0	429.	318.	28.%	25.%
ORTHO-FABRIC* GORETEX + OTHER (PLAIN - 52 X 42)	14.71	.0313	30.0	460.	354.	24.%	7.%

* NOTE: ORTHO-FABRIC TENSILE DATA BASED ON SINGLE SPECIMEN

Table A2. Physical Properties - Substrate Fabrics.

FABRIC ID - CONSTRUCTION (WEAVE - COUNT)	WEIGHT (OZ/SQ YD)	NOMINAL THICKNESS (IN)	AIR PERMEABILITY (CFM)	TENSILE ----(LB)---- WARP	TENSILE FILLING	ELONGATION ----(%)---- WARP	ELONGATION FILLING
15300 DACRON POLYESTER (PLAIN - 41 X 40)	3.29	.0120	930.8	166.	160.	38.%	47.%
15004 DACRON POLYESTER (PLAIN - 108 X 102)	2.19	.0043	174.3	115.	112.	29.%	41.%
15138 DACRON POLYESTER (SATIN - 238 X 74)	5.12	.0087	3.4	232.	279.	37.%	51.%
15364 DACRON POLYESTER (3/1 TWILL - 197 X 144)	3.56	.0043	5.3	206.	163.	32.%	44.%
15530 DACRON POLYESTER (2/2 TWILL - 156 X 57)	8.92	.0168	63.9	411.	258.	29.%	41.%
15782 DACRON POLYESTER (PLAIN - 71 X 68)	3.36	.0075	91.8	143.	130.	22.%	30.%

Table A3. Physical Properties - Flocked Substrates.

Flock ID (Specifications)	Sample Substrate-Flock ID	Flocked Weight (oz/yd^2)	Substrate Weight (oz/yd^2)	Flock + Adhesive Weight (oz/yd^2)	Nominal Thickness (inches)
White Nylon (0.030"; 3 denier)	15300-1	9.6	3.29	6.3	0.0725
	15004-1	8.5	2.19	6.3	0.0558
	15138-1	10.3	5.12	5.2	0.0545
	15364-1	7.9	3.56	4.3	0.0475
	15530-1	16.1	6.92	9.2	0.0628
	15782-1	8.8	3.36	5.4	0.0578
White Nylon (0.045"; 6 denier)	15300-2	10.0	3.29	6.7	0.0705
	15004-2	7.4	2.19	5.2	0.0533
	15138-2	10.5	5.12	5.4	0.0585
	15364-2	8.8	3.56	5.2	0.0558
	15530-2	16.5	6.92	9.6	0.0697
	15782-2	10.3	3.36	6.9	0.0597
White Nylon (0.080"; 20 denier)	15300-3	10.3	3.29	7.0	0.1170
	15004-3	10.3	2.19	8.1	0.1072
	15138-3	13.3	5.12	8.2	0.1000
	15364-3	10.0	8.56	6.4	0.1002
	15530-3	19.2	6.92	12.3	0.0117
	15782-3	11.1	3.36	7.7	0.0988
White Nylon (0.180"; 18 denier)	15300-4	*	3.29	*	*
	15004-4	*	2.19	*	*
	15138-4	12.3	5.12	7.2	0.1885
	15364-4	10.3	3.56	6.7	0.1190
	15530-4	18.2	6.92	11.3	0.1885
	15782-4	10.5	3.36	7.1	0.1418
White Polyester (0.030"; 3 denier)	15300-5	9.9	3.29	6.6	0.0500
	15004-5	5.5	2.19	3.3	0.0332
	15138-5	12.9	5.12	7.8	0.0460
	15364-5	9.0	3.56	5.4	0.0422
	15530-5	18.4	6.92	11.5	0.0515
	15782-5	10.2	3.36	6.8	0.0458

*NOTE: Substrate and flock length were incompatible as noted.

Table A4. Physical Properties - Flocked Blankets.

FABRIC ID *	WEIGHT (OZ/SQ YD)	NOMINAL THICKNESS (IN)	AIR PERMEABILITY (CFM)	TENSILE ----(LB)---- WARP	FILLING	ELONGATION ----(%)---- WARP	FILLING
FIELDCREST SEAFOAM	6.30	.2383	*****	23.	****	59.%	***%
FIELDCREST LIGHT BLUE	6.60	.2245	*****	17.	****	98.%	***%
FIELDCREST ROSE	7.30	.2370	*****	23.	****	68.%	***%
FIELDCREST YELLOW	7.30	.2367	*****	21.	****	61.%	***%
FIELDCREST SANDSTONE	7.00	.2416	*****	21.	****	62.%	***%
FIELDCREST IVORY	6.90	.2307	*****	22.	****	61.%	***%
FIELDCREST COFFEE	6.70	.2120	*****	24.	****	47.%	***%
W.P. PEPPERELL EMERALD	6.20	.2357	*****	30.	****	59.%	***%
W.P. PEPPERELL PINK	7.60	.2503	*****	24.	****	160.%	***%
W.P. PEPPERELL LIGHT GREEN	4.90	.1383	*****	33.	****	52.%	***%

* NOTE: ALL NONWOVEN BLANKET FABRICS MEASURED UNIAXIALLY ONLY
** NOTE: AIR PERMEABILITY NOT MEASURED

Table A5. Physical Properties - Terry Cloths.

FABRIC ID * AND PILE CONFIGURATION	WEIGHT (OZ/SQ YD)	NOMINAL THICKNESS (IN)	AIR PERMEABILITY (CFM)	TENSILE ----(LB)---- WARP	FILLING	ELONGATION ----(%)---- WARP	FILLING
6625 - LIGHTWEIGHT UNSHEARED	12.70	.1593	*****	113.	55.	24.%	18.%
6625 - LIGHTWEIGHT 1 SIDE SHEARED	11.60	.1495	*****	115.	50.	24.%	21.%
6625 - LIGHTWEIGHT 2 SIDES SHEARED	11.30	.1395	*****	117.	56.	26.%	21.%
6883 - MEDIUMWEIGHT UNSHEARED	12.90	.2088	*****	213.	116.	35.%	24.%
6883 - MEDIUMWEIGHT 1 SIDE SHEARED	11.60	.1750	*****	102.	53.	24.%	19.%
6883 - MEDIUMWEIGHT 2 SIDES SHEARED	10.30	.1590	*****	101.	54.	22.%	19.%
6955 - HEAVYWEIGHT UNSHEARED	16.00	.2068	*****	78.	62.	20.%	21.%
6955 - HEAVYWEIGHT 1 SIDE SHEARED	13.20	.1918	*****	76.	60.	20.%	23.%
6955 - HEAVYWEIGHT 2 SIDES SHEARED	11.00	.1818	*****	76.	66.	19.%	25.%
1000 - KNITTED UNSHEARED	12.40	.2003	*****	107.	73.	42.%	52.%
1000 - KNITTED 1 SIDE SHEARED	11.30	.1838	*****	105.	75.	40.%	58.%
1000 - KNITTED 2 SIDES SHEARED	10.40	.1753	*****	107.	74.	44.%	55.%

* NOTE: AIR PERMEABILITY NOT MEASURED

APPENDIX B

THICKNESS VS. PRESSURE

Table B1. Thickness vs. Pressure - PTFE Fabrics.

SAMPLE ID	TEFLON T187-30			TEFLON T162-42			TEFLON T388-43			GORETEX 604			ORTHO FABRIC		
FABRIC WEIGHT	4.50 (OZ/SQ YD)			9.92 (OZ/SQ YD)			10.14 (OZ/SQ YD)			8.61 (OZ/SQ YD)			14.71 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.0053			.0097			.0110			.0123			.0313		
.100	.0056	100.0	1.07	.0100	100.0	1.33	.0113	100.0	1.20	.0113	100.0	1.02	.0276	100.0	.71
.200	.0056	98.8	1.08	.0099	99.3	1.34	.0109	96.5	1.24	.0109	96.5	1.05	.0269	97.3	.73
.350	.0055	97.6	1.09	.0098	98.7	1.35	.0110	97.3	1.23	.0108	95.9	1.06	.0260	94.1	.76
.500	.0053	93.5	1.14	.0096	96.3	1.38	.0108	95.3	1.26	.0109	96.8	1.05	.0256	92.6	.77
.750	.0052	92.3	1.16	.0095	95.7	1.39	.0105	93.2	1.29	.0104	91.7	1.11	.0252	91.2	.78
1.000	.0051	91.1	1.17	.0093	93.3	1.42	.0105	92.6	1.29	.0103	91.2	1.12	.0248	89.7	.79
1.500	.0052	92.3	1.16	.0097	97.3	1.37	.0105	93.2	1.29	.0104	91.7	1.11	.0245	88.8	.80
2.000	.0051	89.9	1.19	.0094	94.3	1.41	.0104	92.0	1.30	.0104	92.0	1.11	.0241	87.1	.82
2.500	.0050	88.8	1.20	.0092	92.0	1.44	.0100	88.5	1.35	.0100	88.5	1.15	.0237	85.6	.83
3.000	.0049	86.4	1.23	.0092	92.3	1.44	.0100	88.8	1.35	.0100	88.8	1.15	.0235	85.2	.83

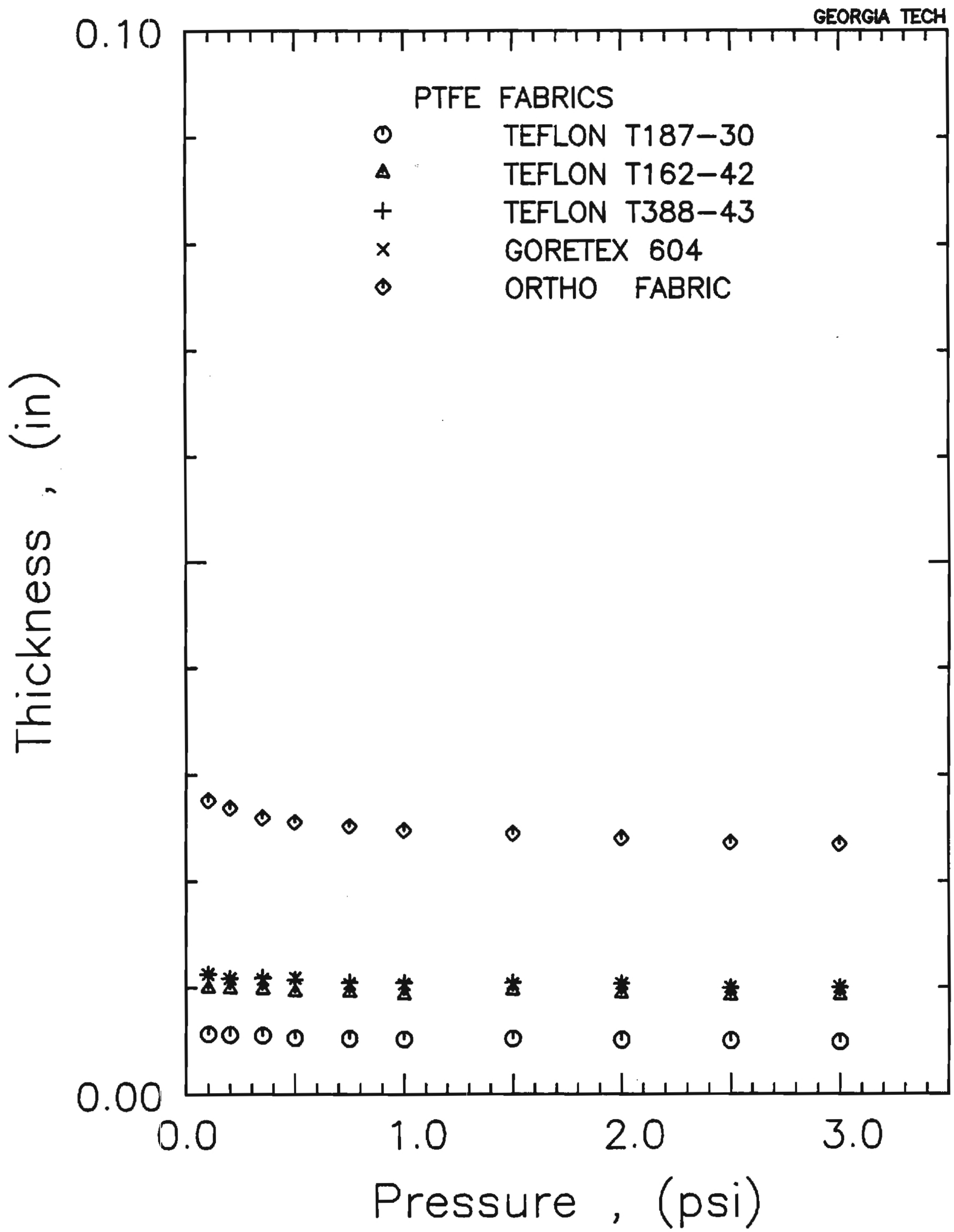

Figure B1. Thickness vs. Pressure - PTFE Fabrics.

Table B2. Thickness vs. Pressure - Substrate Fabrics, Group 1.

	SUBSTRATE			SUBSTRATE			SUBSTRATE		
SAMPLE ID	15300			15004			15138		
FABRIC WEIGHT	3.29 (OZ/SQ YD)			2.19 (OZ/SQ YD)			5.12 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.0120			.0043			.0087		
.100	.0125	100.0	.35	.0048	100.0	.61	.0091	100.0	.75
.200	.0124	99.5	.35	.0049	102.1	.60	.0092	101.1	.74
.350	.0125	100.3	.35	.0050	104.2	.58	.0092	100.4	.75
.500	.0124	99.7	.35	.0049	102.8	.59	.0093	101.5	.74
.750	.0124	99.2	.36	.0049	101.4	.60	.0094	102.6	.73
1.000	.0123	98.7	.36	.0046	96.5	.63	.0090	98.2	.76
1.500	.0122	97.9	.36	.0047	97.9	.62	.0090	98.9	.76
2.000	.0119	95.5	.37	.0049	102.1	.60	.0092	101.1	.74
2.500	.0118	94.9	.37	.0048	100.7	.60	.0090	98.5	.76
3.000	.0117	93.9	.38	.0045	94.4	.64	.0089	97.1	.77

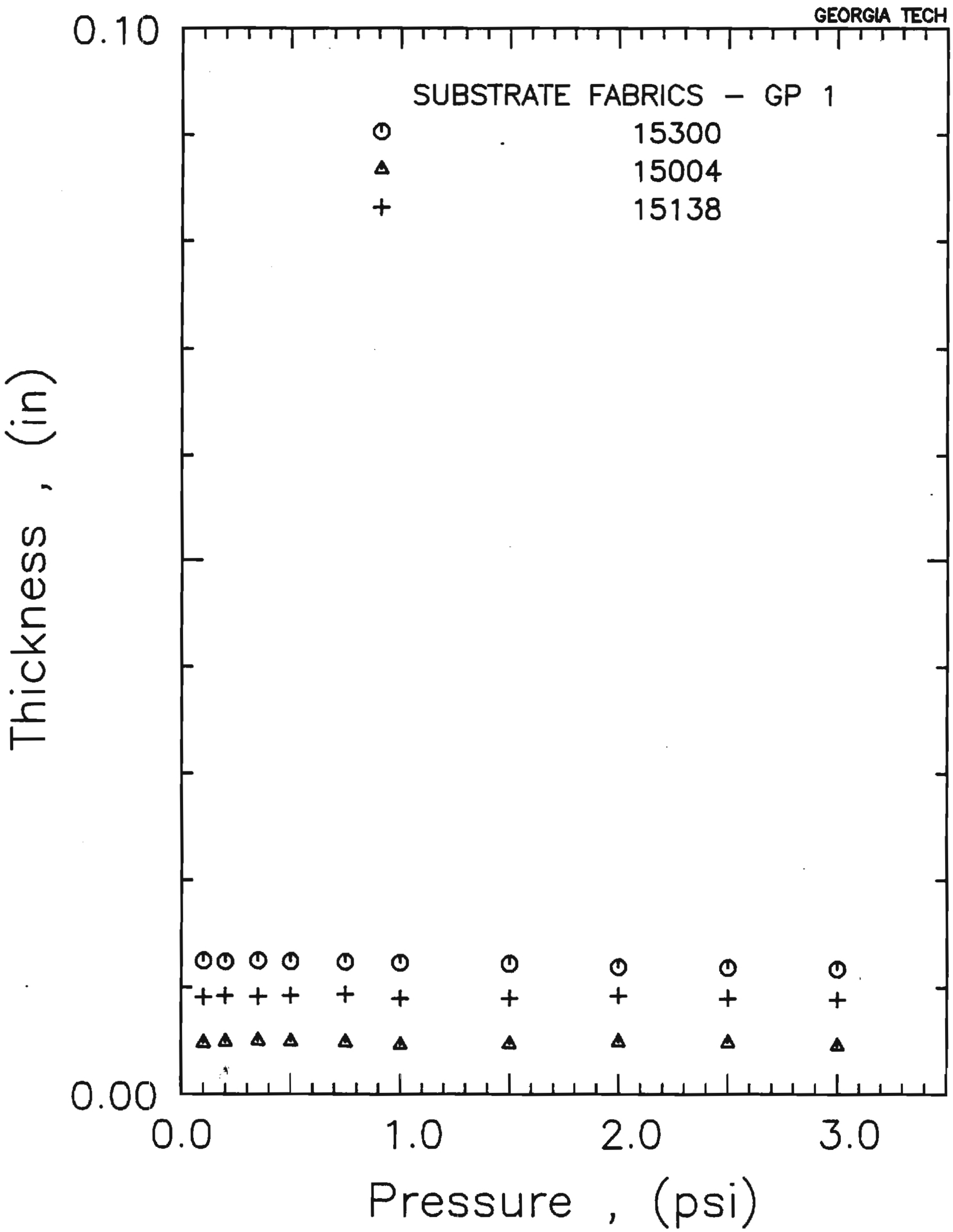

Figure B.2. Thickness vs. Pressure - Substrate Fabrics, Group 1.

Table B3. Thickness vs. Pressure - Substrate Fabrics, Group 2.

SAMPLE ID	SUBSTRATE 15364			SUBSTRATE 15530			SUBSTRATE 15782		
FABRIC WEIGHT	3.56 (OZ/SQ YD)			6.92 (OZ/SQ YD)			3.36 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.0043			.0168			.0075		
.100	.0048	100.0	.99	.0173	100.0	.69	.0070	100.0	.64
.200	.0049	102.1	.97	.0172	99.6	.69	.0069	99.0	.65
.350	.0048	100.7	.98	.0172	99.2	.69	.0062	88.5	.73
.500	.0049	102.8	.96	.0171	98.8	.70	.0061	87.6	.74
.750	.0049	101.4	.98	.0170	98.5	.70	.0062	89.0	.72
1.000	.0046	96.5	1.03	.0170	98.1	.70	.0060	85.6	.75
1.500	.0047	97.9	1.01	.0172	99.4	.69	.0059	84.2	.76
2.000	.0047	98.6	1.00	.0174	100.6	.68	.0059	84.7	.76
2.500	.0047	97.2	1.02	.0170	98.3	.70	.0057	81.3	.79
3.000	.0045	94.4	1.05	.0170	98.5	.70	.0055	79.4	.81

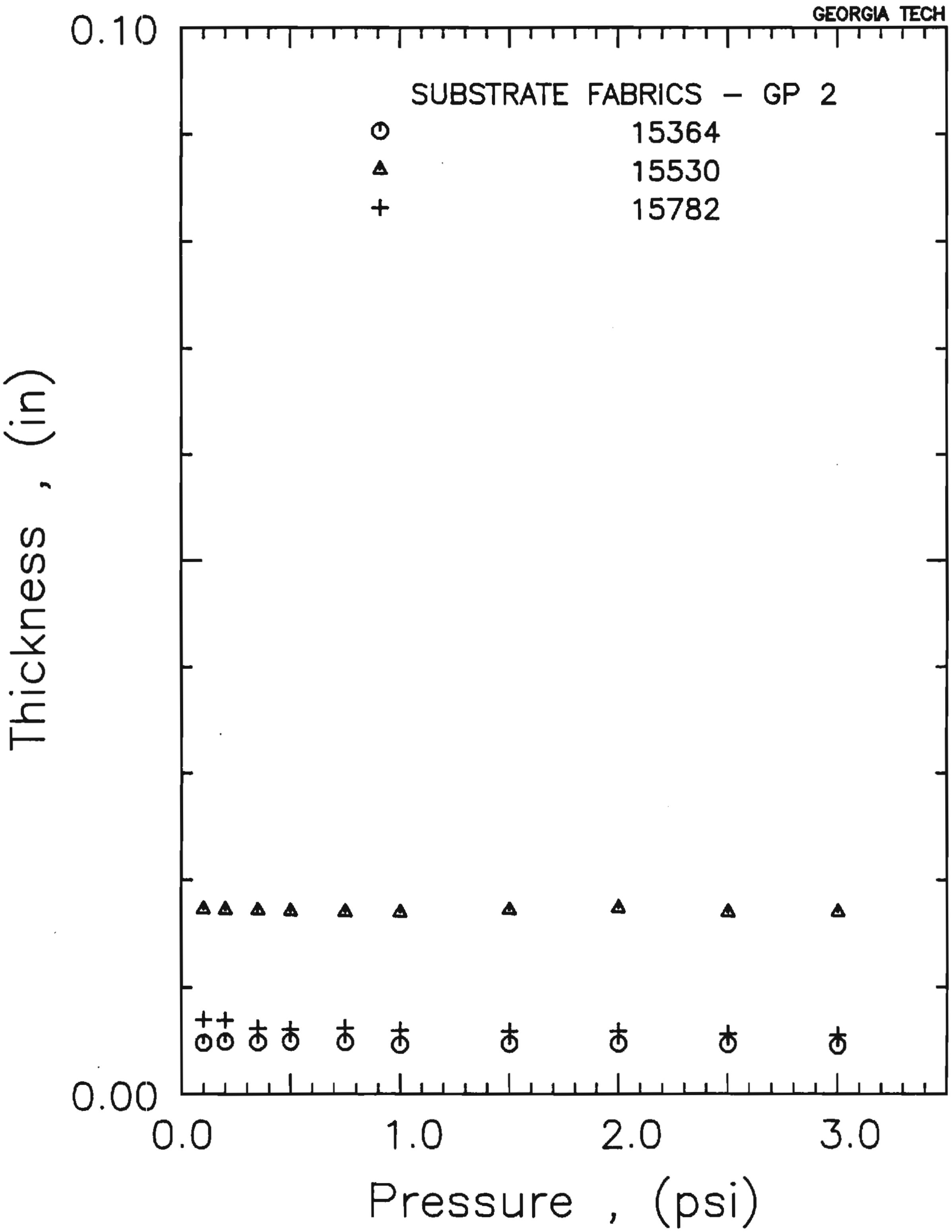

Figure B3. Thickness vs. Pressure - Substrate Fabrics, Group 2.

Table B4. Thickness vs. Pressure - Flocked Substrate 15300.

SAMPLE ID	FLOCKED 15300-1			FLOCKED 15300-2			FLOCKED 15300-3			FLOCKED 15300-5		
FABRIC WEIGHT	9.60 (OZ/SQ YD)			10.00 (OZ/SQ YD)			10.30 (OZ/SQ YD)			9.90 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.0725			.0705			.1170			.0500		
.100	.0626	100.0	.20	.0610	100.0	.22	.1063	100.0	.13	.0438	100.0	.30
.200	.0589	94.0	.22	.0586	96.1	.23	.1027	96.6	.13	.0412	94.1	.32
.350	.0557	88.9	.23	.0568	93.2	.23	.0992	93.3	.14	.0397	90.6	.33
.500	.0531	84.8	.24	.0556	91.2	.24	.0969	91.2	.14	.0388	88.5	.34
.750	.0512	81.7	.25	.0545	89.4	.24	.0937	88.1	.15	.0377	86.1	.35
1.000	.0493	78.7	.26	.0530	86.9	.25	.0895	84.2	.15	.0366	83.6	.36
1.500	.0482	77.0	.27	.0514	84.3	.26	.0830	78.1	.17	.0350	80.0	.38
2.000	.0462	73.8	.28	.0502	82.4	.27	.0734	69.0	.19	.0327	74.7	.40
2.500	.0448	71.6	.29	.0492	80.6	.27	.0642	60.4	.21	.0317	72.3	.42
3.000	.0435	69.5	.29	.0479	78.5	.28	.0584	54.9	.24	.0305	69.7	.43

NOTE: SUBSTRATE AND FLOCK LENGTH WERE INCOMPATIBLE FOR SPECIMEN 15300-4.

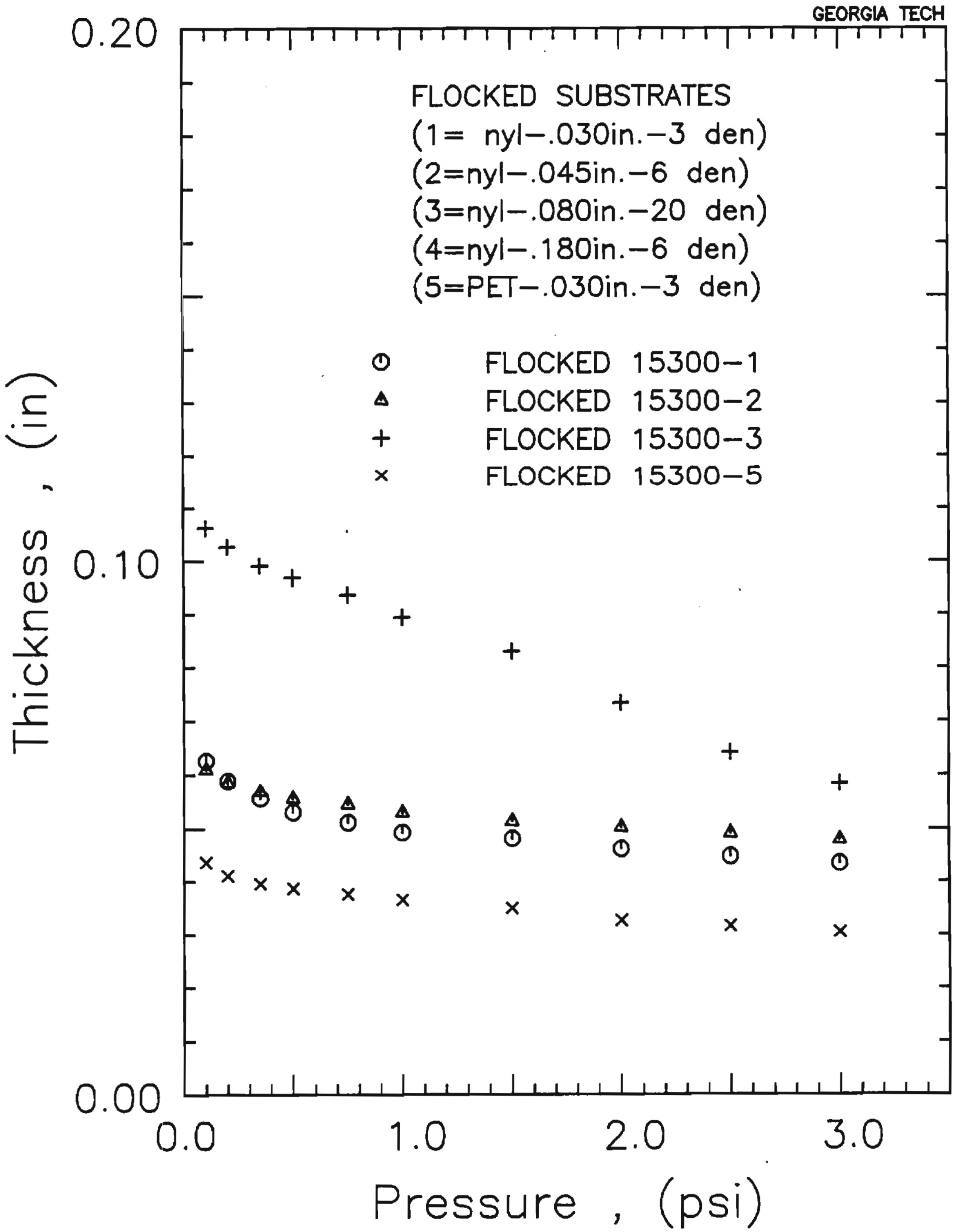

Figure B4. Thickness vs. Pressure - Flocked Substrate 15300.

Table B5. Thickness vs. Pressure - Flocked Substrate 15004.

SAMPLE ID	FLOCKED 15004-1			FLOCKED 15004-2			FLOCKED 15004-3			FLOCKED 15004-5		
FABRIC WEIGHT	8.50 (OZ/SQ YD)			7.40 (OZ/SQ YD)			10.30 (OZ/SQ YD)			5.50 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.0558			.0535			.1072			.0332		
.100	.0496	100.0	.23	.0501	100.0	.20	.0990	100.0	.14	.0306	100.0	.24
.200	.0472	95.2	.24	.0489	97.5	.20	.0976	98.6	.14	.0296	96.5	.25
.350	.0460	92.7	.25	.0478	95.4	.21	.0952	96.2	.14	.0285	93.0	.26
.500	.0448	90.2	.25	.0471	93.9	.21	.0938	94.7	.15	.0273	89.0	.27
.750	.0437	88.0	.26	.0462	92.2	.21	.0925	93.5	.15	.0250	81.7	.29
1.000	.0425	85.6	.27	.0450	89.7	.22	.0905	91.4	.15	.0230	75.0	.32
1.500	.0405	81.7	.28	.0444	88.5	.22	.0894	90.3	.15	.0187	61.0	.39
2.000	.0384	77.4	.30	.0432	86.2	.23	.0871	88.0	.16	.0164	53.5	.45
2.500	.0357	71.9	.32	.0418	83.4	.24	.0853	86.2	.16	.0155	50.6	.47
3.000	.0340	68.6	.33	.0407	81.2	.24	.0837	84.6	.16	.0150	49.1	.49

NOTE: SUBSTRATE AND FLOCK LENGTH WERE INCOMPATIBLE FOR SPECIMEN 15004-4.

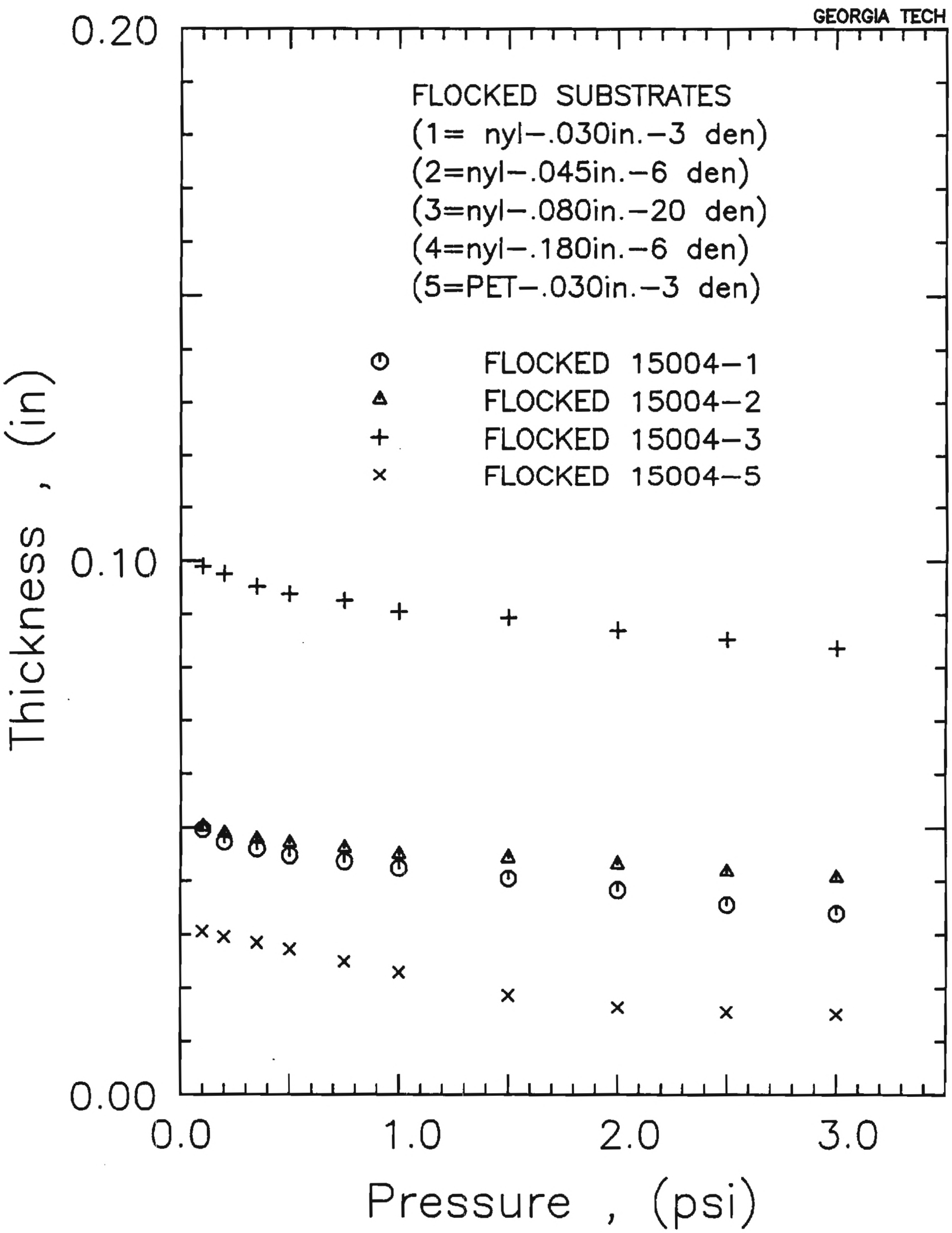

Figure B5. Thickness vs. Pressure - Flocked Substrate 15004.

Table B6. Thickness vs. Pressure - Flocked Substrate 15138.

SAMPLE ID	FLOCKED 15138-1			FLOCKED 15138-2			FLOCKED 15138-3			FLOCKED 15138-4			FLOCKED 15138-5		
FABRIC WEIGHT	10.30 (OZ/SQ YD)			10.50 (OZ/SQ YD)			13.30 (OZ/SQ YD)			12.30 (OZ/SQ YD)			12.90 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.0545			.0585			.1000			.1885			.0460		
.100	.0503	100.0	.27	.0551	100.0	.25	.0961	100.0	.18	.1571	100.0	.10	.0406	100.0	.42
.200	.0489	97.2	.28	.0534	96.9	.26	.0946	98.4	.19	.1492	95.0	.11	.0392	96.6	.44
.350	.0475	94.4	.29	.0520	94.3	.27	.0925	96.2	.19	.1407	89.5	.12	.0383	94.3	.45
.500	.0464	92.3	.30	.0509	92.4	.28	.0901	93.7	.20	.1016	64.7	.16	.0379	93.4	.45
.750	.0452	89.9	.30	.0499	90.4	.28	.0854	88.8	.21	.0684	43.5	.24	.0372	91.6	.46
1.000	.0440	87.4	.31	.0485	87.9	.29	.0756	78.7	.23	.0591	37.6	.28	.0360	88.5	.48
1.500	.0415	82.6	.33	.0469	85.0	.30	.0639	66.4	.28	.0519	33.0	.32	.0354	87.0	.49
2.000	.0377	75.0	.36	.0449	81.4	.31	.0536	55.7	.33	.0467	29.7	.35	.0339	83.4	.51
2.500	.0343	68.3	.40	.0422	76.5	.33	.0498	51.8	.36	.0425	27.0	.39	.0325	80.0	.53
3.000	.0324	64.3	.42	.0400	72.6	.35	.0475	49.4	.37	.0404	25.7	.41	.0305	75.1	.56

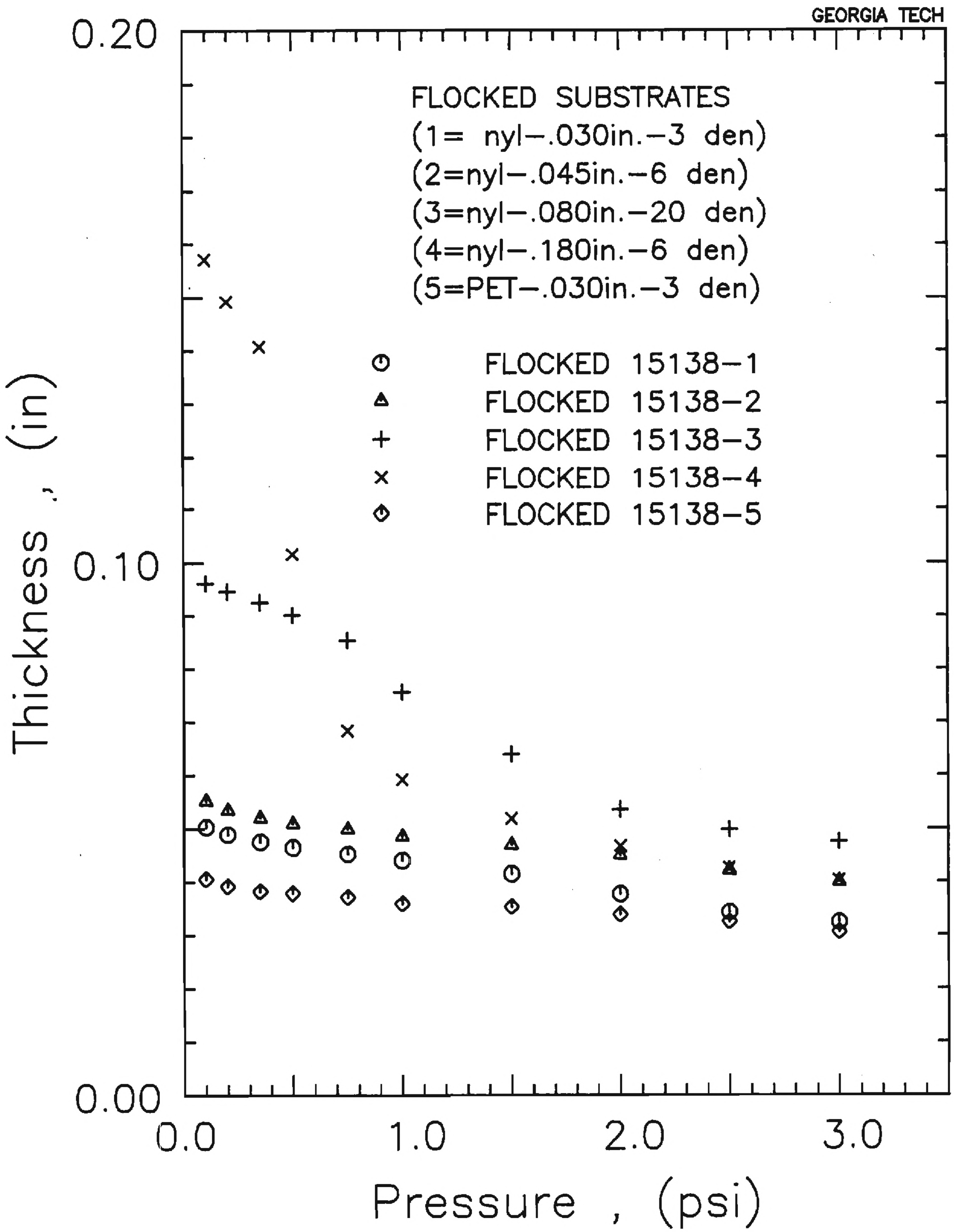

Figure B6. Thickness vs. Pressure - Flocked Substrate 15138.

Table B7. Thickness vs. Pressure - Flocked Substrate 15364.

SAMPLE ID	FLOCKED 15364-1			FLOCKED 15364-2			FLOCKED 15364-3			FLOCKED 15364-4			FLOCKED 15364-5		
FABRIC WEIGHT	7.90 (OZ/SQ YD)			8.60 (OZ/SQ YD)			10.00 (OZ/SQ YD)			10.30 (OZ/SQ YD)			9.00 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.0475			.0558			.1002			.1190			.0422		
.100	.0443	100.0	.24	.0518	100.0	.23	.0963	100.0	.14	.0723	100.0	.19	.0358	100.0	.34
.200	.0432	97.6	.24	.0501	96.7	.23	.0941	97.7	.14	.0604	83.5	.23	.0351	98.0	.34
.350	.0415	93.7	.25	.0490	94.6	.24	.0922	95.7	.14	.0523	72.4	.26	.0343	95.9	.35
.500	.0403	90.9	.26	.0483	93.2	.24	.0903	93.7	.15	.0496	68.6	.28	.0336	93.9	.36
.750	.0384	86.6	.27	.0474	91.4	.25	.0887	92.1	.15	.0449	62.1	.31	.0330	92.3	.36
1.000	.0370	83.4	.29	.0465	89.7	.25	.0865	89.8	.15	.0413	57.1	.33	.0323	90.2	.37
1.500	.0329	74.2	.32	.0457	88.2	.26	.0830	86.2	.16	.0379	52.4	.36	.0317	88.5	.38
2.000	.0304	68.6	.35	.0446	86.0	.26	.0722	75.0	.18	.0356	49.2	.39	.0309	86.3	.39
2.500	.0278	62.6	.38	.0438	84.6	.27	.0617	64.0	.22	.0338	46.8	.41	.0300	83.8	.40
3.000	.0262	59.1	.40	.0425	82.1	.28	.0582	60.4	.23	.0325	45.0	.42	.0292	81.6	.41

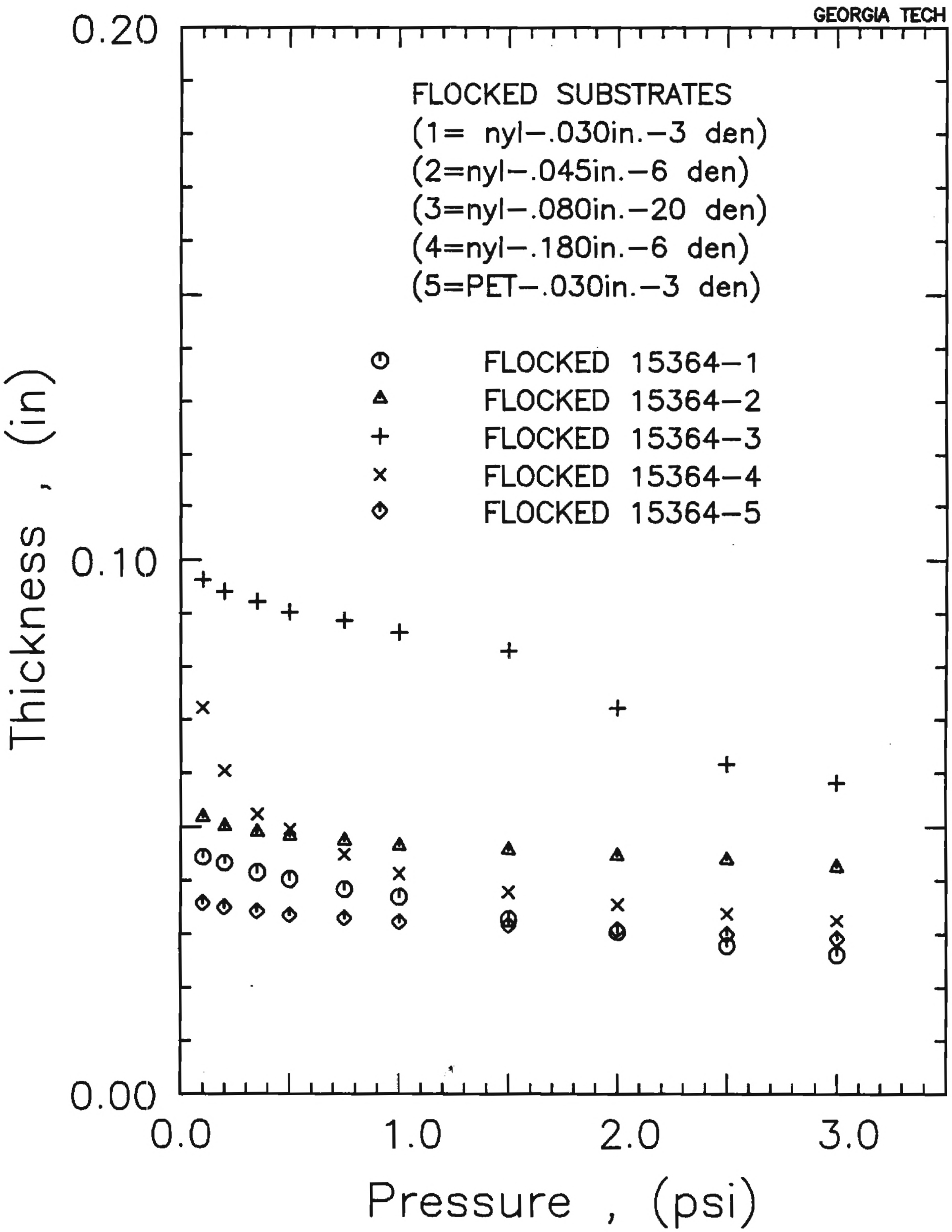

Figure B7. Thickness vs. Pressure - Flocked Substrate 15364.

Table B9. Thickness vs. Pressure - Flocked Substrate 15782.

SAMPLE ID	FLOCKED 15530-1			FLOCKED 15530-2			FLOCKED 15530-3			FLOCKED 15530-4			FLOCKED 15530-5		
FABRIC WEIGHT	16.10 (OZ/SQ YD)			16.50 (OZ/SQ YD)			19.20 (OZ/SQ YD)			18.20 (OZ/SQ YD)			18.40 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.0628			.0697			.1167			.1885			.0515		
.100	.0583	100.0	.37	.0623	100.0	.35	.1063	100.0	.24	.1640	100.0	.15	.0468	100.0	.52
.200	.0559	95.9	.38	.0602	96.7	.37	.1041	97.9	.25	.1499	91.4	.16	.0461	98.4	.53
.350	.0545	93.5	.39	.0587	94.2	.38	.1017	95.6	.25	.1177	71.8	.21	.0452	96.5	.54
.500	.0529	90.8	.41	.0579	93.0	.38	.1003	94.3	.26	.0808	49.3	.30	.0444	94.9	.55
.750	.0515	88.4	.42	.0572	91.8	.39	.0979	92.1	.26	.0699	42.6	.35	.0435	93.0	.56
1.000	.0501	86.0	.43	.0560	89.8	.39	.0963	90.6	.27	.0623	38.0	.39	.0428	91.5	.57
1.500	.0484	83.0	.44	.0549	88.1	.40	.0934	87.8	.27	.0564	34.4	.43	.0414	88.4	.59
2.000	.0452	77.6	.48	.0536	86.0	.41	.0832	78.3	.31	.0521	31.8	.47	.0402	86.0	.61
2.500	.0423	72.6	.51	.0525	84.3	.42	.0773	72.8	.33	.0495	30.2	.49	.0395	84.4	.62
3.000	.0395	67.8	.54	.0510	81.9	.43	.0715	67.3	.36	.0475	29.0	.51	.0367	78.4	.67

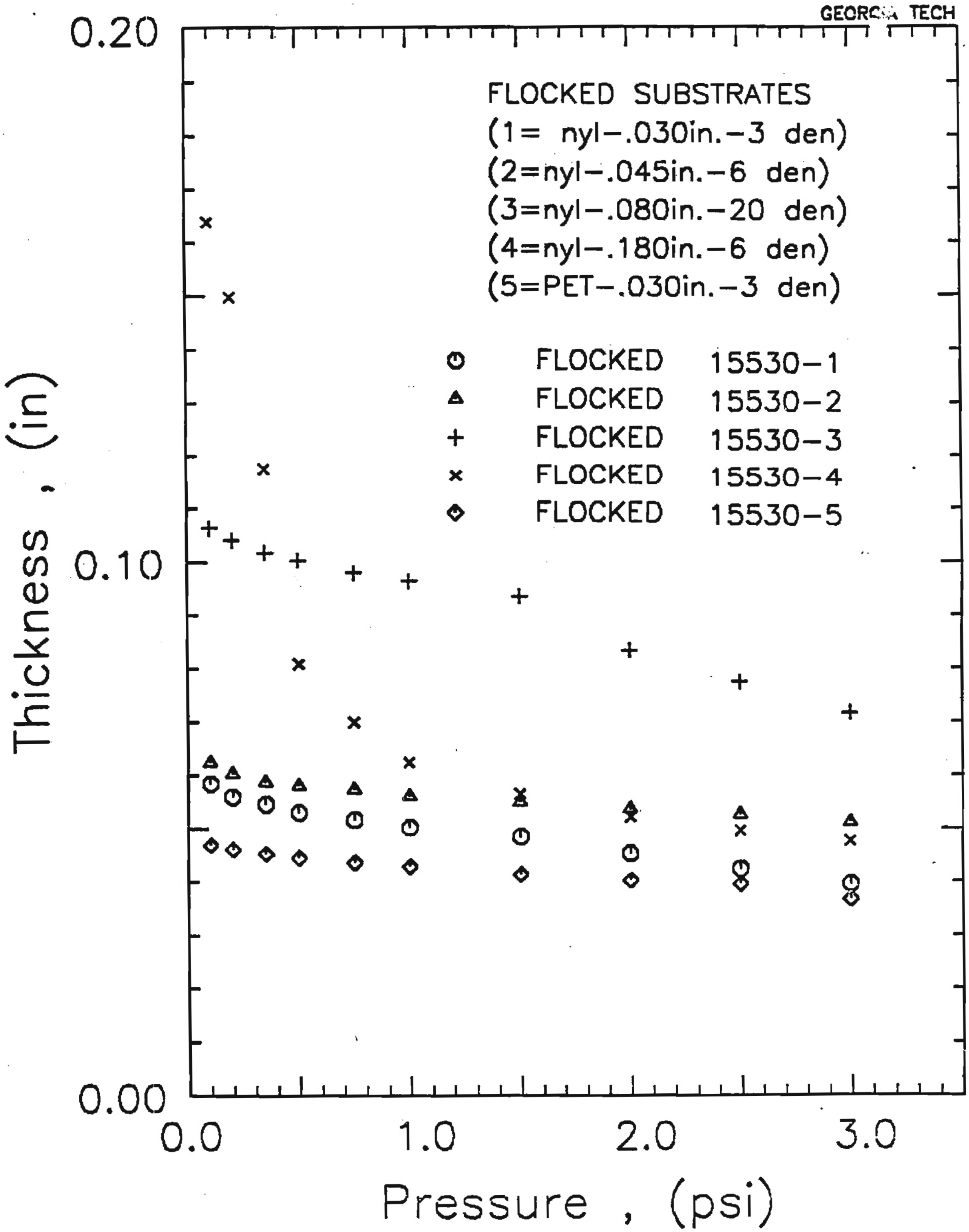

Figure B8. Thickness vs. Pressure - Flocked Substrate 15530.

Table B9. Thickness vs. Pressure - Flocked Substrate 15782.

SAMPLE ID	FLOCKED 15782-1			FLOCKED 15782-2			FLOCKED 15782-3			FLOCKED 15782-4			FLOCKED 15782-5		
FABRIC WEIGHT	8.80 (OZ/SQ YD)			10.30 (OZ/SQ YD)			11.10 (OZ/SQ YD)			10.50 (OZ/SQ YD)			10.20 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.0578			.0597			.0988			.1418			.0458		
.100	.0525	100.0	.22	.0516	100.0	.27	.0945	100.0	.16	.0950	100.0	.15	.0405	100.0	.34
.200	.0501	95.4	.23	.0499	96.6	.28	.0926	98.0	.16	.0815	85.8	.17	.0386	95.3	.35
.350	.0483	92.1	.24	.0487	94.3	.28	.0908	96.1	.16	.0625	65.8	.22	.0375	92.7	.36
.500	.0473	90.1	.25	.0474	91.9	.29	.0888	94.0	.17	.0571	60.1	.25	.0368	90.9	.37
.750	.0462	88.1	.25	.0467	90.4	.29	.0854	90.4	.17	.0517	54.4	.27	.0360	89.0	.38
1.000	.0448	85.4	.26	.0445	86.1	.31	.0823	87.1	.18	.0465	48.9	.30	.0353	87.2	.39
1.500	.0434	82.7	.27	.0425	82.4	.32	.0629	66.5	.24	.0430	45.3	.33	.0344	84.9	.40
2.000	.0421	80.2	.28	.0384	74.4	.36	.0539	57.1	.27	.0399	42.0	.35	.0337	83.4	.40
2.500	.0398	75.9	.29	.0357	69.1	.39	.0500	52.9	.30	.0383	40.4	.37	.0328	81.1	.41
3.000	.0387	73.8	.30	.0329	63.7	.42	.0472	50.0	.31	.0365	38.5	.38	.0322	79.6	.42

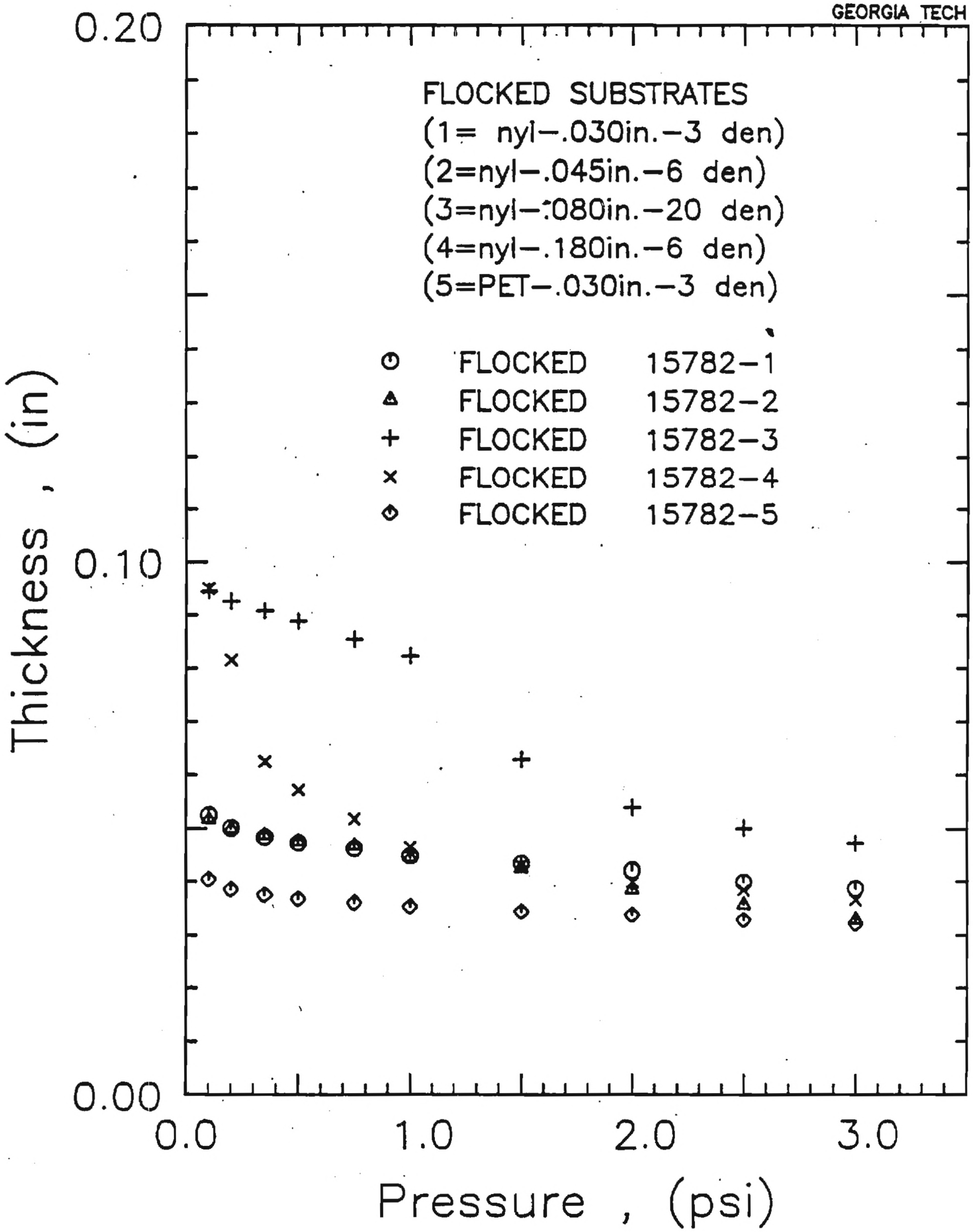

Figure B9. Thickness vs. Pressure - Flocked Substrate 15782.

Table B10. Thickness vs. Pressure - Flocked Blankets, Group 1.

SAMPLE ID	FIELDCREST- SEAFOAM			FIELDCREST- LT BLUE			FIELDCREST- ROSE			FIELDCREST- YELLOW			FIELDCREST- SANDSTONE		
FABRIC WEIGHT	8.30 (OZ/SQ YD)			6.60 (OZ/SQ YD)			7.30 (OZ/SQ YD)			7.30 (OZ/SQ YD)			7.00 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.2383			.2245			.2370			.2367			.2417		
.100	.2231	100.0	.05	.2021	100.0	.04	.2231	100.0	.04	.2198	100.0	.04	.2263	100.0	.04
.200	.2061	92.4	.05	.1657	82.0	.05	.2106	94.4	.05	.1967	89.5	.05	.2156	95.3	.04
.350	.1823	81.7	.06	.1462	72.3	.06	.1848	82.8	.05	.1698	77.3	.06	.1870	82.6	.05
.500	.1693	75.9	.07	.1358	67.2	.06	.1604	71.9	.06	.1563	71.1	.06	.1601	70.7	.06
.750	.1565	70.2	.07	.1189	58.8	.07	.1332	59.7	.07	.1412	64.2	.07	.1337	59.1	.07
1.000	.1326	59.4	.08	.0956	47.3	.09	.1065	47.7	.09	.1115	50.7	.09	.1103	48.7	.08
1.500	.1045	46.8	.11	.0759	37.5	.12	.0822	36.8	.12	.0885	40.3	.11	.0837	37.0	.11
2.000	.0899	40.3	.12	.0657	32.5	.13	.0697	31.3	.14	.0759	34.5	.13	.0699	30.9	.13
2.500	.0800	35.9	.14	.0580	28.7	.15	.0605	27.1	.16	.0670	30.5	.15	.0607	26.8	.15
3.000	.0729	32.7	.15	.0527	26.1	.17	.0544	24.4	.18	.0607	27.6	.16	.0549	24.2	.17

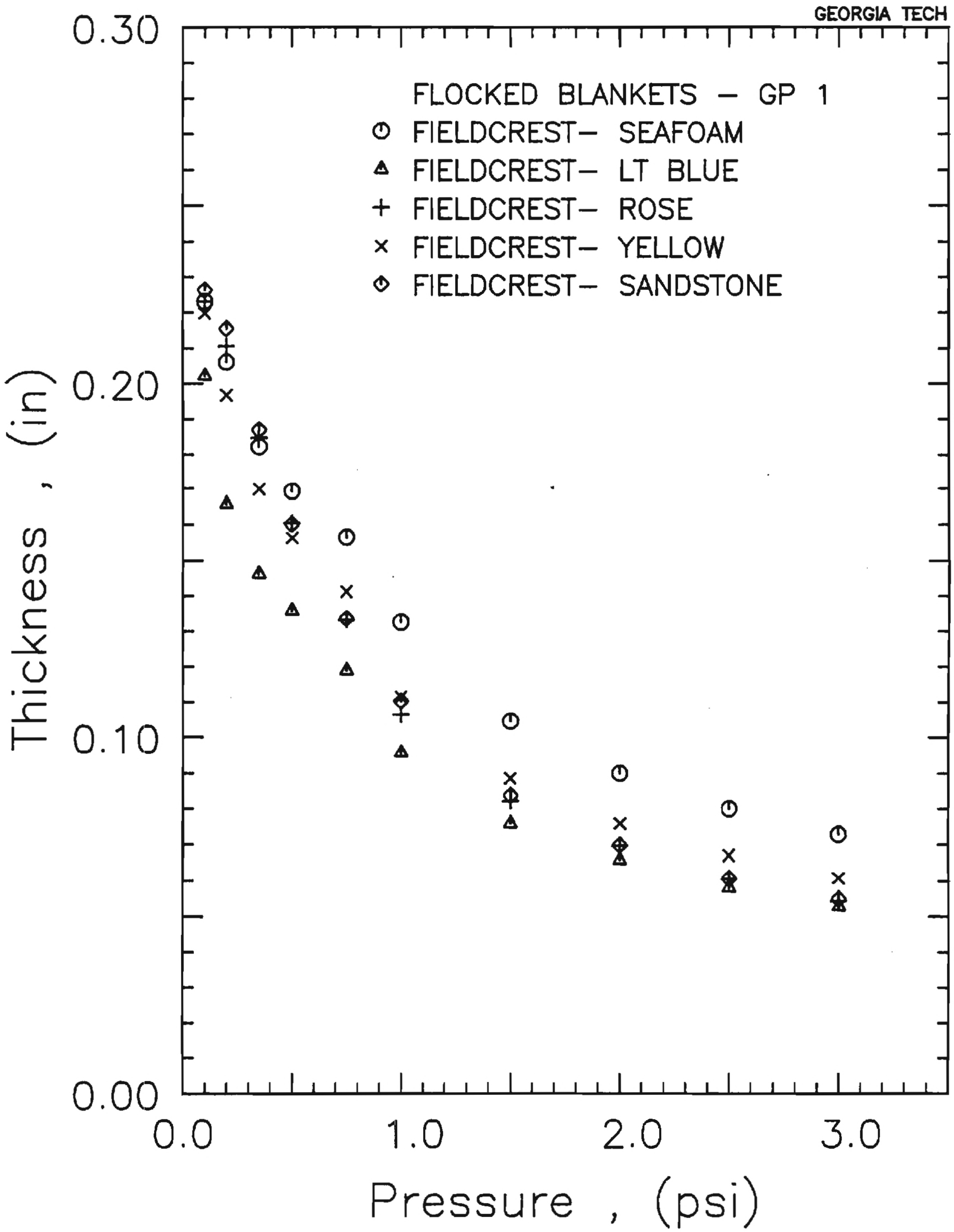

Figure B10. Thickness vs. Pressure - Flocked Blankets, Group 1.

Table B11. Thickness vs. Pressure - Flocked Blankets, Group 2.

SAMPLE ID	FIELDCREST-IVORY			FIELDCREST-COFFEE			WP PEPPERELL - EMERALD			WP PEPPERELL - PINK			WP PEPPERELL - LT GREEN		
FABRIC WEIGHT	6.90 (OZ/SQ YD)			6.70 (OZ/SQ YD)			8.20 (OZ/SQ YD)			7.60 (OZ/SQ YD)			4.90 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.2307			.2120			.2357			.2503			.1383		
.100	.2135	100.0	.04	.1906	100.0	.05	.2188	100.0	.05	.2373	100.0	.04	.1303	100.0	.05
.200	.1857	87.0	.05	.1582	83.0	.06	.1962	89.7	.06	.2117	89.2	.05	.1227	94.2	.05
.350	.1698	79.6	.05	.1365	71.6	.07	.1718	78.5	.06	.1775	74.8	.06	.1175	90.2	.06
.500	.1544	72.3	.06	.1201	63.0	.07	.1568	71.6	.07	.1576	66.4	.06	.1109	85.1	.06
.750	.1314	61.5	.07	.0982	51.5	.09	.1392	63.6	.08	.1437	60.6	.07	.0944	72.4	.07
1.000	.1066	50.0	.09	.0786	41.2	.11	.1153	52.7	.09	.1153	48.6	.09	.0751	57.7	.09
1.500	.0850	39.8	.11	.0625	32.8	.14	.0900	41.1	.12	.0882	37.2	.12	.0594	45.6	.11
2.000	.0722	33.8	.13	.0536	28.1	.17	.0761	34.8	.14	.0737	31.1	.14	.0499	38.3	.13
2.500	.0638	29.9	.14	.0480	25.2	.19	.0672	30.7	.16	.0645	27.2	.16	.0438	33.6	.15
3.000	.0570	26.7	.16	.0439	23.0	.20	.0614	28.0	.18	.0584	24.6	.17	.0402	30.9	.16

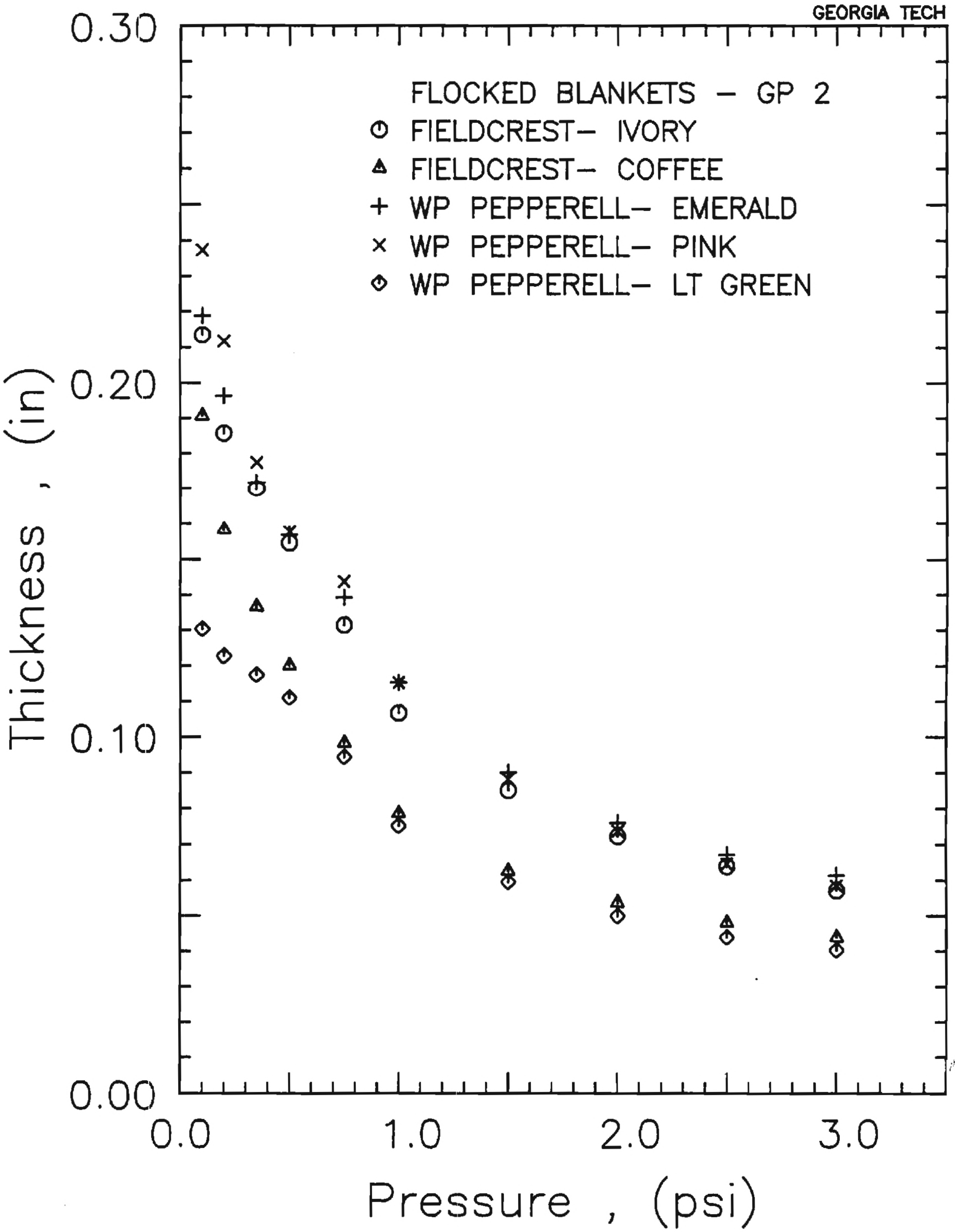

Figure B11. Thickness vs. Pressure - Flocked Blankets, Group 2.

Table B12. Thickness vs. Pressure - Terry Cloth, Lightweight.

SAMPLE ID	UNSHEARED 6625			1 SHEARED 6625			2 SHEARED 6625		
FABRIC WEIGHT	12.70 (OZ/SQ YD)			11.60 (OZ/SQ YD)			11.30 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.1593			.1495			.1395		
.100	.1183	100.0	.14	.1161	100.0	.13	.1096	100.0	.14
.200	.1097	92.8	.15	.1029	88.6	.15	.0992	90.5	.15
.350	.0953	80.6	.18	.0938	80.8	.17	.0893	81.5	.17
.500	.0901	76.2	.19	.0844	72.7	.18	.0799	72.9	.19
.750	.0829	70.0	.20	.0777	66.9	.20	.0744	67.8	.20
1.000	.0756	63.9	.22	.0715	61.5	.22	.0681	62.1	.22
1.500	.0709	59.9	.24	.0670	57.7	.23	.0629	57.3	.24
2.000	.0662	56.0	.26	.0621	53.4	.25	.0589	53.7	.26
2.500	.0627	53.0	.27	.0592	50.9	.26	.0567	51.7	.27
3.000	.0605	51.2	.28	.0569	49.0	.27	.0544	49.6	.28

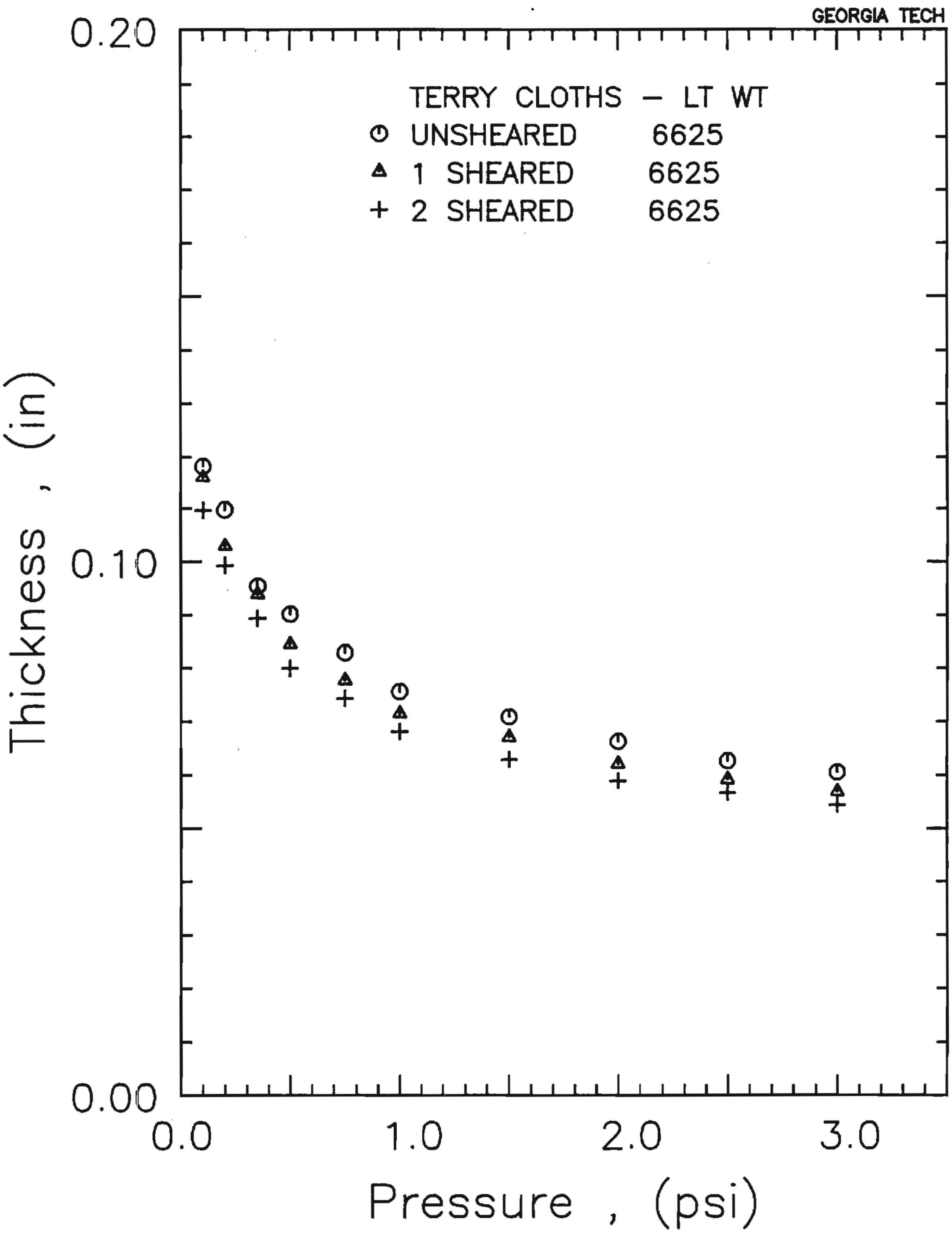

Figure B12. Thickness vs. Pressure - Terry Cloth, Lightweight.

Table B13. Thickness vs. Pressure - Terry Cloth, Medium Weight.

SAMPLE ID	UNSHEARED 6883			1 SHEARED 6883			2 SHEARED 6883		
FABRIC WEIGHT	12.90 (OZ/SQ YD)			11.60 (OZ/SQ YD)			10.30 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.2068			.1750			.1590		
.100	.1710	100.0	.10	.1478	100.0	.10	.1345	100.0	.10
.200	.1559	91.2	.11	.1354	91.6	.11	.1181	87.8	.12
.350	.1382	80.8	.12	.1203	81.4	.13	.1038	77.2	.13
.500	.1266	74.0	.14	.1084	73.4	.14	.0943	70.1	.15
.750	.1145	67.0	.15	.0982	66.4	.16	.0815	60.6	.17
1.000	.1026	60.0	.17	.0880	59.5	.18	.0730	54.3	.19
1.500	.0914	53.4	.19	.0775	52.5	.20	.0659	49.0	.21
2.000	.0844	49.4	.20	.0714	48.3	.22	.0604	44.9	.23
2.500	.0788	46.1	.22	.0667	45.1	.23	.0573	42.6	.24
3.000	.0749	43.8	.23	.0634	42.9	.24	.0547	40.7	.25

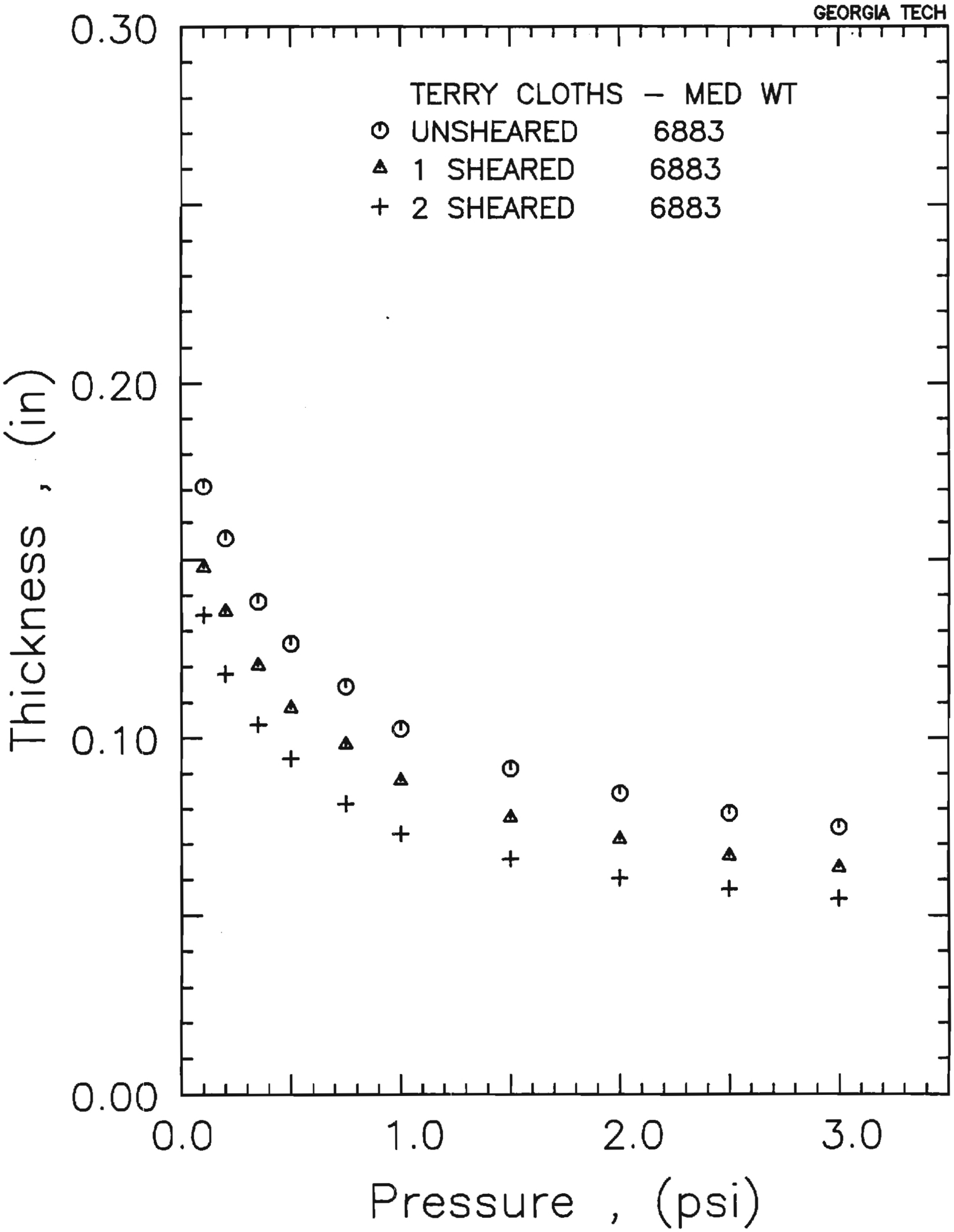

Figure B13. Thickness vs. Pressure - Terry Cloth, Medium Weight.

Table B14. Thickness vs. Pressure - Terry Cloth, Heavyweight.

SAMPLE ID	UNSHEARED 6955			1 SHEARED 6955			2 SHEARED 6955		
FABRIC WEIGHT	16.00 (OZ/SQ YD)			13.20 (OZ/SQ YD)			11.00 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.2068			.1918			.1818		
.100	.1655	100.0	.13	.1500	100.0	.12	.1430	100.0	.10
.200	.1544	93.3	.14	.1411	94.1	.12	.1276	89.2	.12
.350	.1415	85.5	.15	.1265	84.4	.14	.1092	76.4	.13
.500	.1324	80.0	.16	.1168	77.9	.15	.0964	67.5	.15
.750	.1215	73.4	.16	.1072	71.5	.16	.0857	59.9	.17
1.000	.1126	68.1	.19	.0976	65.1	.18	.0775	54.2	.19
1.500	.1039	62.8	.21	.0880	58.7	.20	.0695	48.6	.21
2.000	.0972	58.8	.22	.0809	53.9	.22	.0651	45.5	.23
2.500	.0920	55.6	.23	.0767	51.1	.23	.0613	42.9	.24
3.000	.0862	53.3	.24	.0730	48.7	.24	.0592	41.4	.25

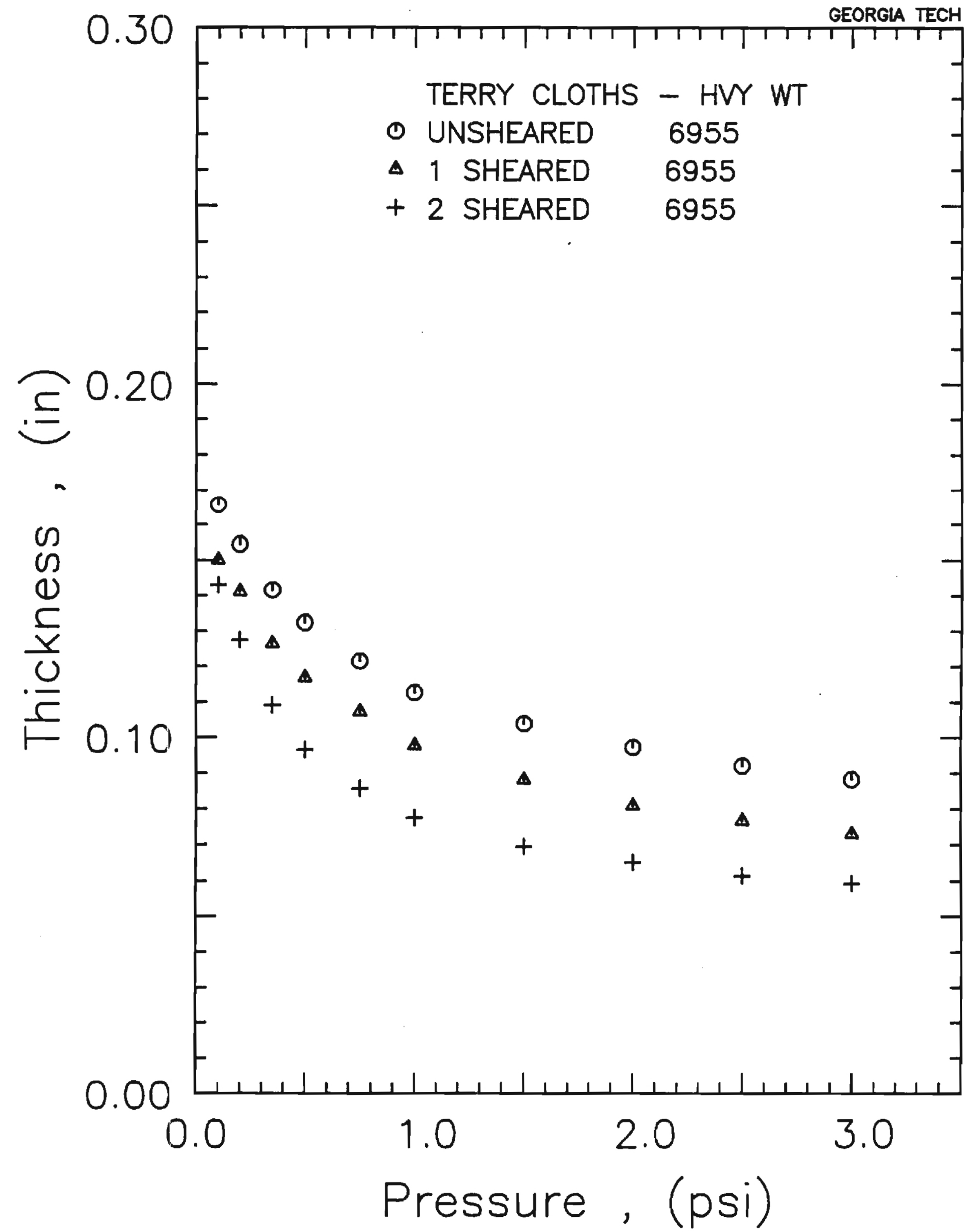

Figure B14. Thickness vs. Pressure - Terry Cloth, Heavyweight.

Table B15. Thickness vs. Pressure - Terry Cloth, Knitted.

SAMPLE ID	UNSHEARED 1000			1 SHEARED 1000			2 SHEARED 1000		
FABRIC WEIGHT	12.40 (OZ/SQ YD)			11.30 (OZ/SQ YD)			10.40 (OZ/SQ YD)		
APPLIED PRESSURE (PSI)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)	THK (IN)	% THK	DEN (GM/CC)
NOM	.2003			.1838			.1753		
.100	.1593	100.0	.10	.1516	100.0	.10	.1438	100.0	.10
.200	.1374	86.3	.12	.1282	84.6	.12	.1289	89.6	.11
.350	.1235	77.5	.13	.1122	74.0	.13	.1042	72.4	.13
.500	.1154	72.5	.14	.1011	66.7	.15	.0914	63.6	.15
.750	.1025	64.4	.16	.0902	59.5	.17	.0832	57.9	.17
1.000	.0931	58.5	.18	.0810	53.4	.19	.0753	52.4	.18
1.500	.0847	53.2	.20	.0732	48.3	.21	.0687	47.8	.20
2.000	.0789	49.5	.21	.0679	44.8	.22	.0629	43.7	.22
2.500	.0737	46.2	.22	.0640	42.2	.24	.0600	41.7	.23
3.000	.0710	44.6	.23	.0617	40.7	.24	.0577	40.1	.24

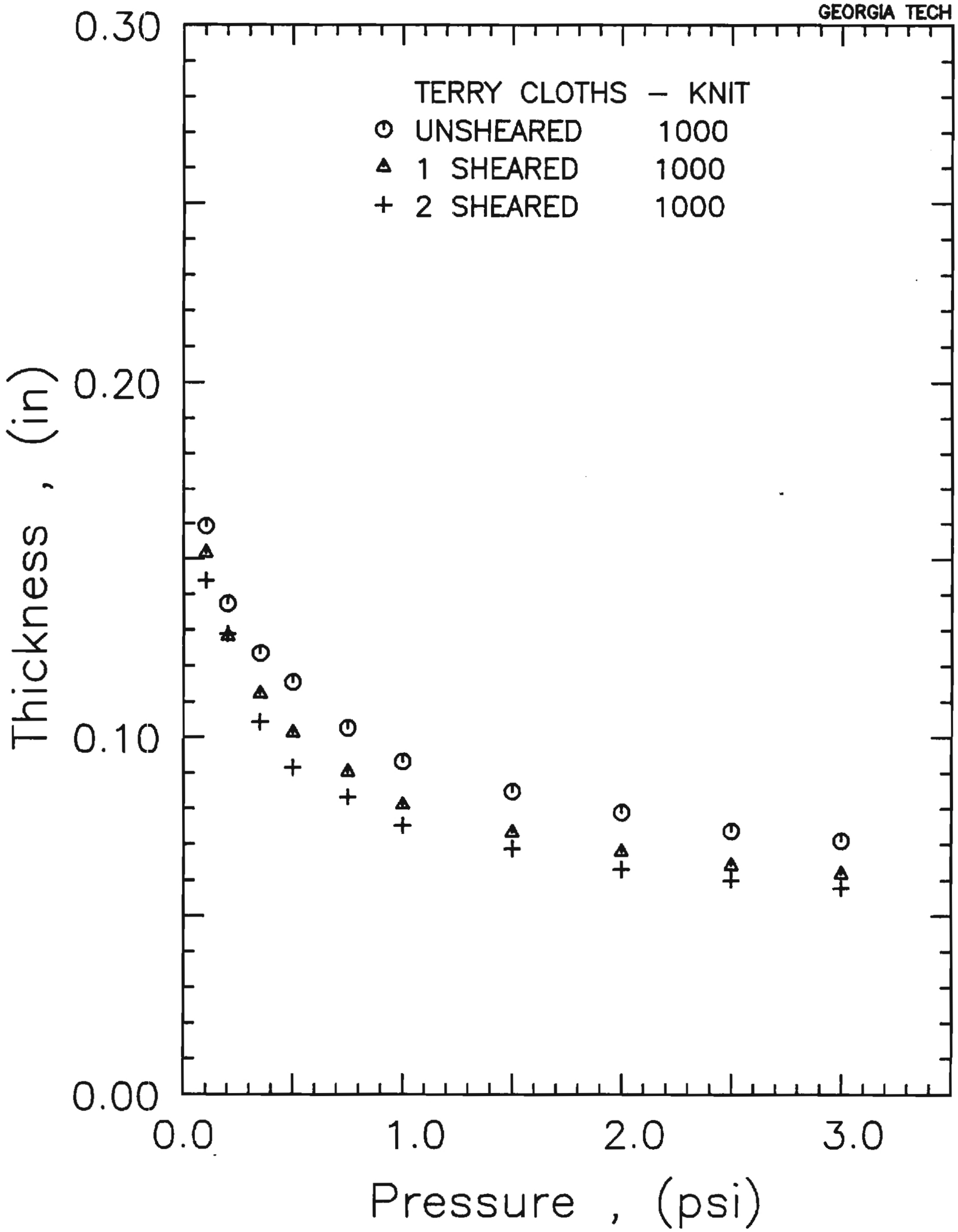

Figure B15. Thickness vs. Pressure - Terry Cloth, Knitted.

APPENDIX C

THERMAL DATA

COMPOSITE LAYUPS, GROUPS 1, 2 AND 3

Table C1. Thermal Data - Composite Layups, Group 1.

APPLIED PRESSURE (PSI)	THICKNESS (IN)	T 1 (LOWER) (DEG C)	T 2 (UPPER) (DEG C)	HEAT FLUX (BTU/HR-FT2)	DEL T (DEG F)	CONDUCTANCE (FLUX/DEG F)	CONDUCTIVITY (FLUX*FT/DEG F)	R-VALUE (HR-FT2-DEG F/BTU)
		TITLE FORMAT = (OUTER LAYER)-(MIDDLE LAYER)-(INNER LAYER)						
1. SAMPLE ID =		ORTHO-NONE-LOW FLOCK						
NOM	.0780	100.	81.	135.5	34.2	3.96	.026	.25
.200	.0580	101.	88.	147.0	23.4	5.28	.030	.15
2. SAMPLE ID =		ORTHO-NONE-HIGH FLOCK						
NOM	.1241	100.	77.	124.0	41.4	3.00	.031	.33
.200	.1039	100.	81.	131.5	34.2	3.85	.033	.26
3. SAMPLE ID =		604 -NONE-LOW FLOCK						
NOM	.0560	99.	83.	147.5	28.8	5.12	.024	.20
.200	.0432	100.	89.	149.5	19.8	7.55	.027	.13
4. SAMPLE ID =		604 -NONE-HIGH FLOCK						
NOM	.1058	99.	75.	136.0	43.2	3.15	.028	.32
.200	.0906	99.	79.	141.0	36.0	3.92	.030	.26

*NOTE: Low Flock = Short Flock = 15364-1.
High Flock = Long Flock = 15364-3.

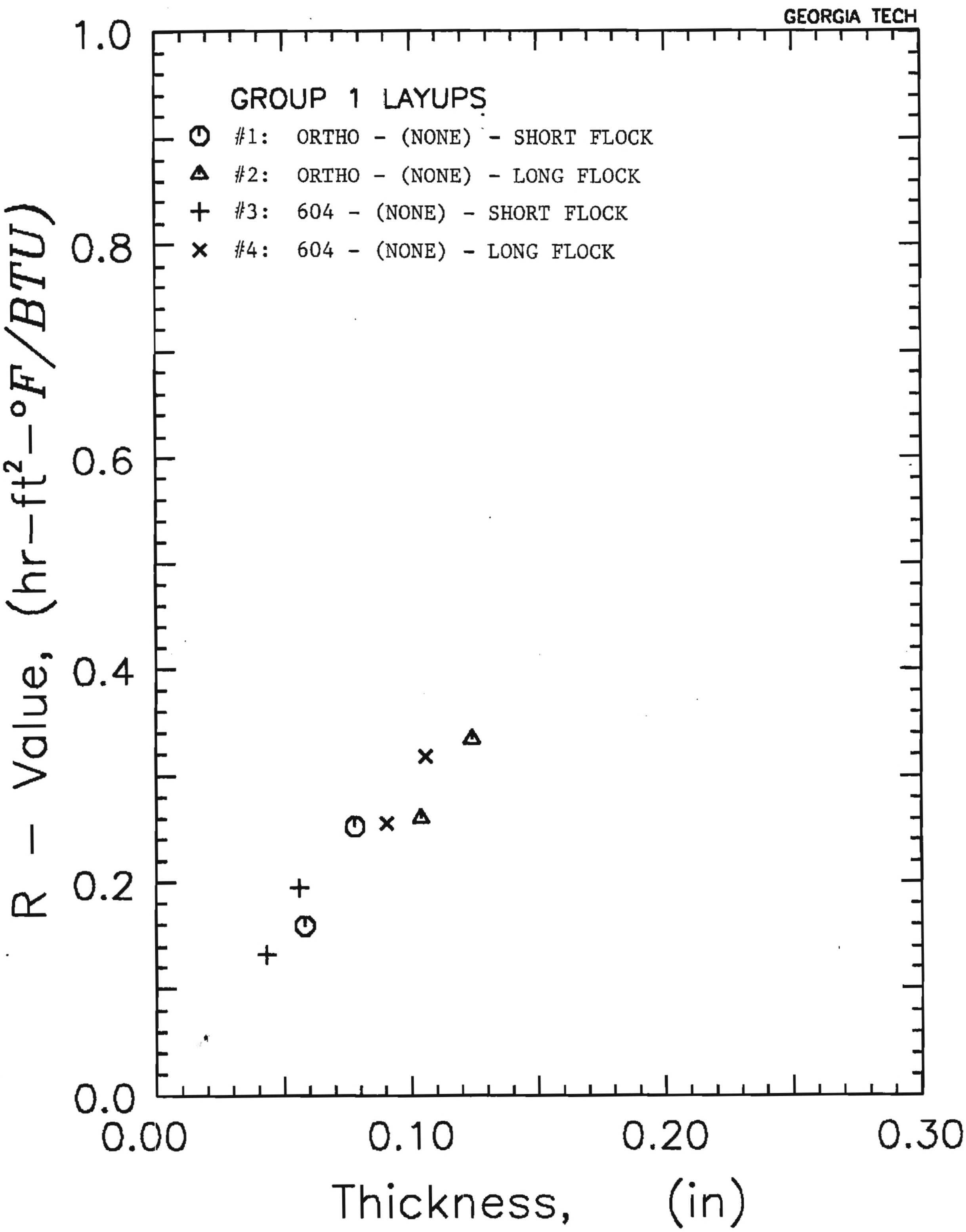

Figure C1. R Value vs. Thickness - Composite Layups, Group 1.

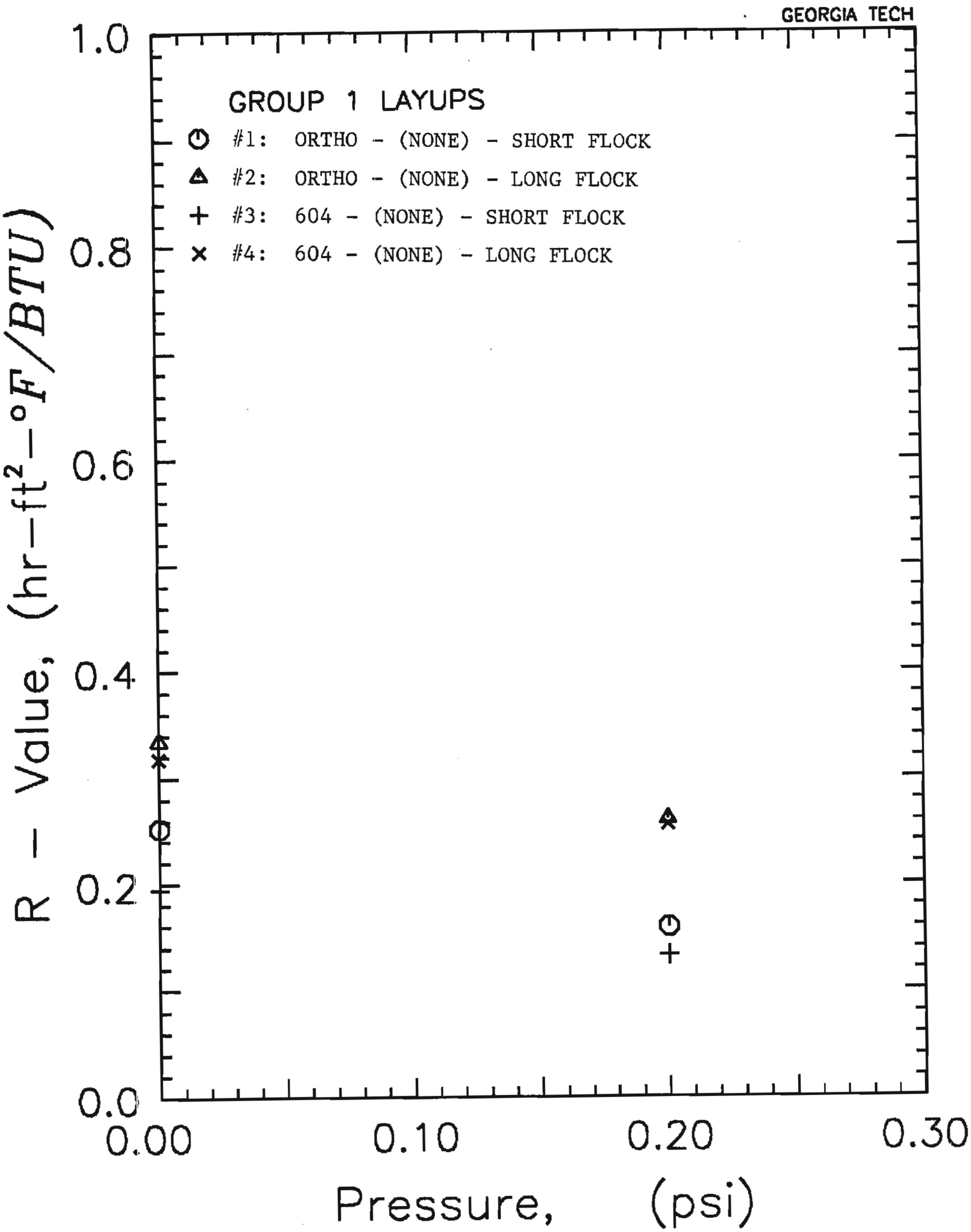

Figure C2. R Value vs. Pressure - Composite Layups, Group 1.

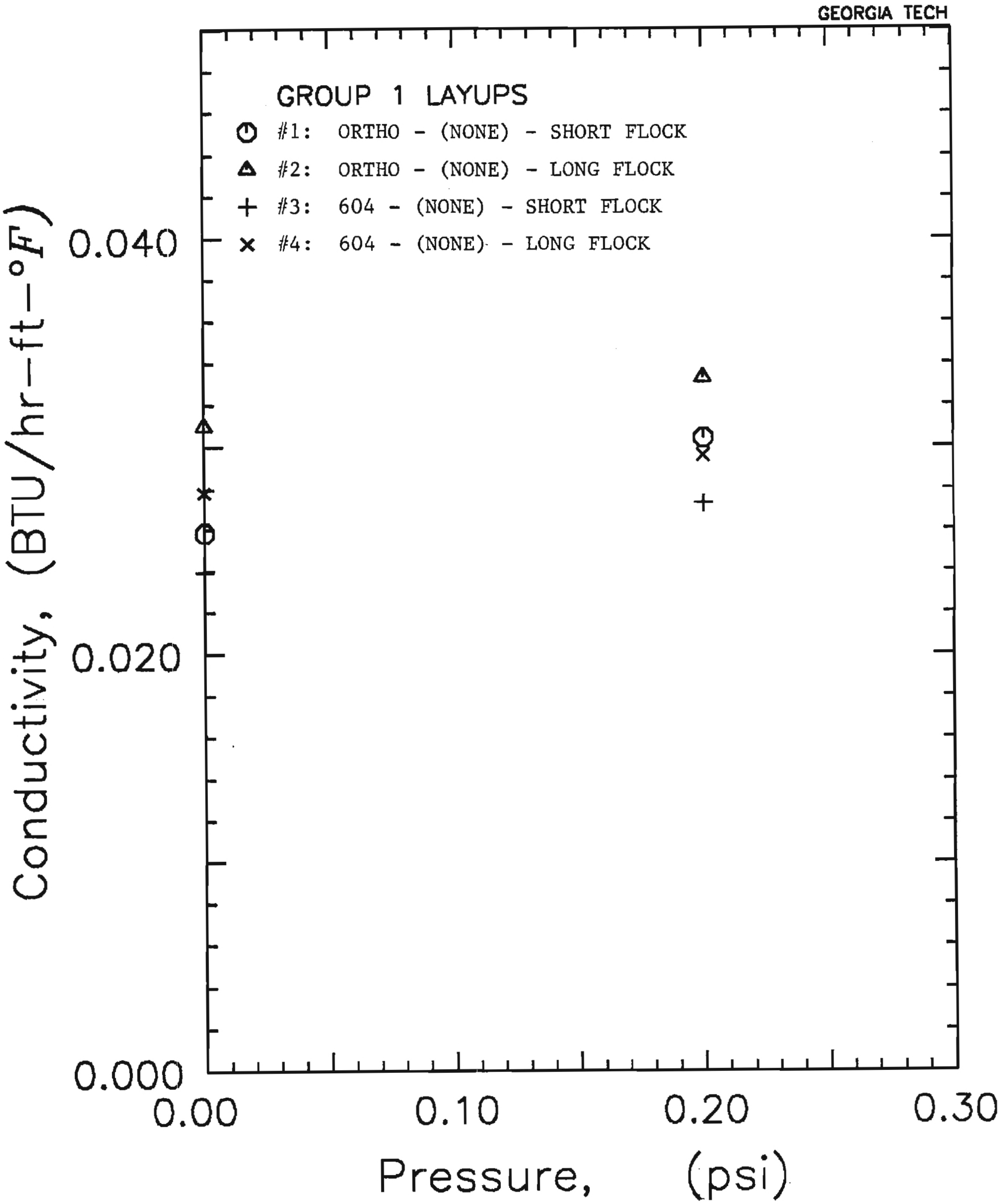

Figure C3. Conductivity vs. Pressure - Composite Layups, Group 1.

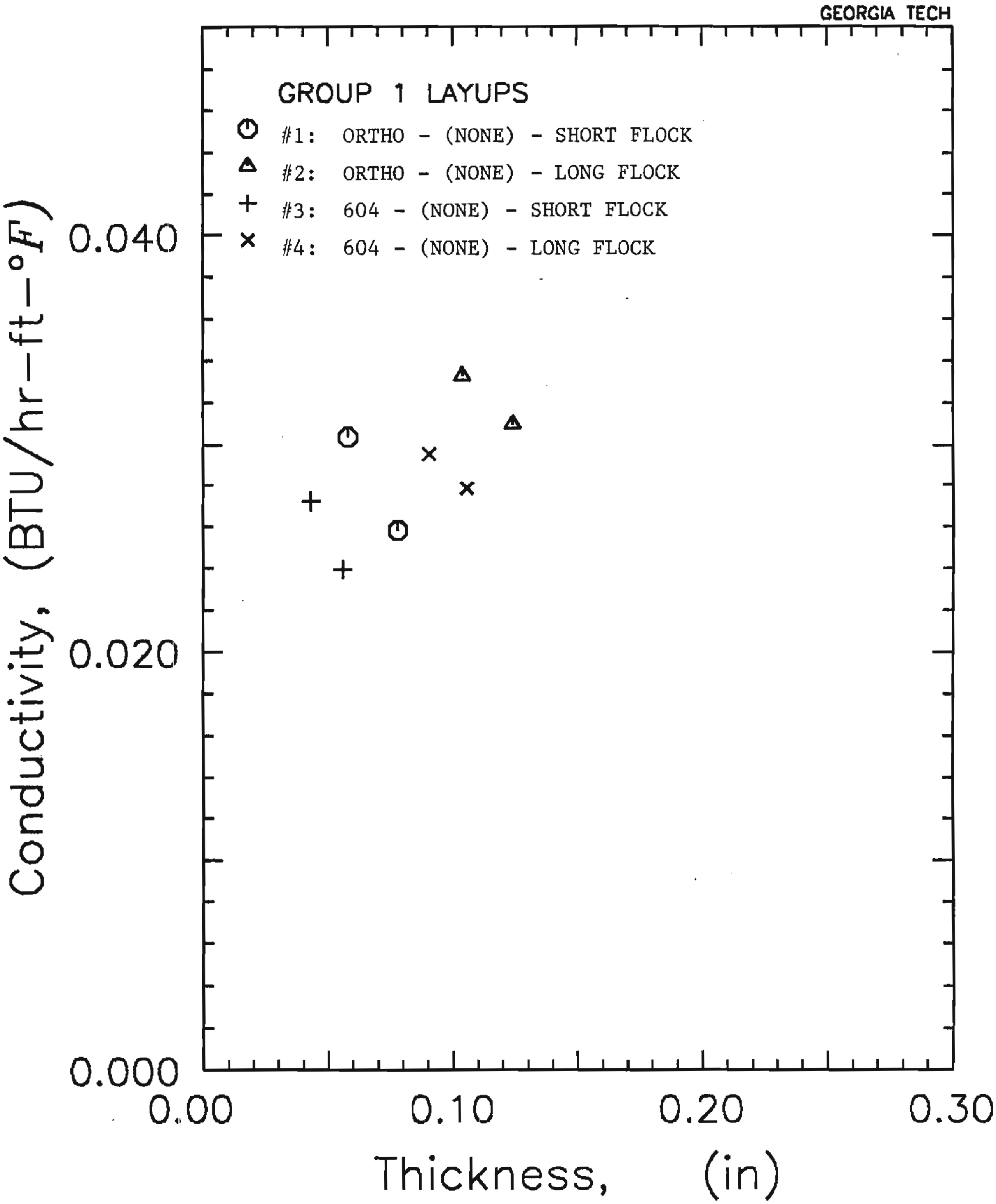

Figure C4. Conductivity vs. Thickness - Composite Layups, Group 1.

Table C2. Thermal Data - Composite Layups, Group 2.

APPLIED PRESSURE (PSI)	THICKNESS (IN)	T 1 (LOWER) (DEG C)	T 2 (UPPER) (DEG C)	HEAT FLUX (BTU/HR-FT2)	DEL T (DEG F)	CONDUCTANCE (FLUX/DEG F)	CONDUCTIVITY (FLUX*FT/DEG F)	R-VALUE (HR-FT2-DEG F/BTU)
		TITLE FORMAT = (OUTER LAYER)-(MIDDLE LAYER)-(INNER LAYER)						
5. SAMPLE ID =		604 - 1 FILM-LOW FLOCK						
NOM	.0658	100.	83.	138.0	30.6	4.51	.025	.22
.200	.0497	100.	88.	148.5	21.6	6.88	.028	.15
6. SAMPLE ID =		604 - 1 FILM-HIGH FLOCK						
NOM	.1127	101.	77.	125.5	43.2	2.91	.027	.34
.200	.0945	100.	81.	133.5	34.2	3.90	.031	.26
7. SAMPLE ID =		604 -LOW FLOCK-LOW FLOCK						
NOM	.0994	100.	80.	129.0	36.0	3.58	.030	.28
.200	.0728	100.	86.	139.0	25.2	5.52	.033	.18
8. SAMPLE ID =		604 -HIGH FLOCK-HIGH FLOCK						
NOM	.1584	100.	74.	125.5	46.8	2.68	.035	.37
.200	.1243	100.	79.	133.0	37.8	3.52	.036	.26

*NOTE: Low Flock = Short Flock = 15364-1.
High Flock = Long Flock = 15364-3.

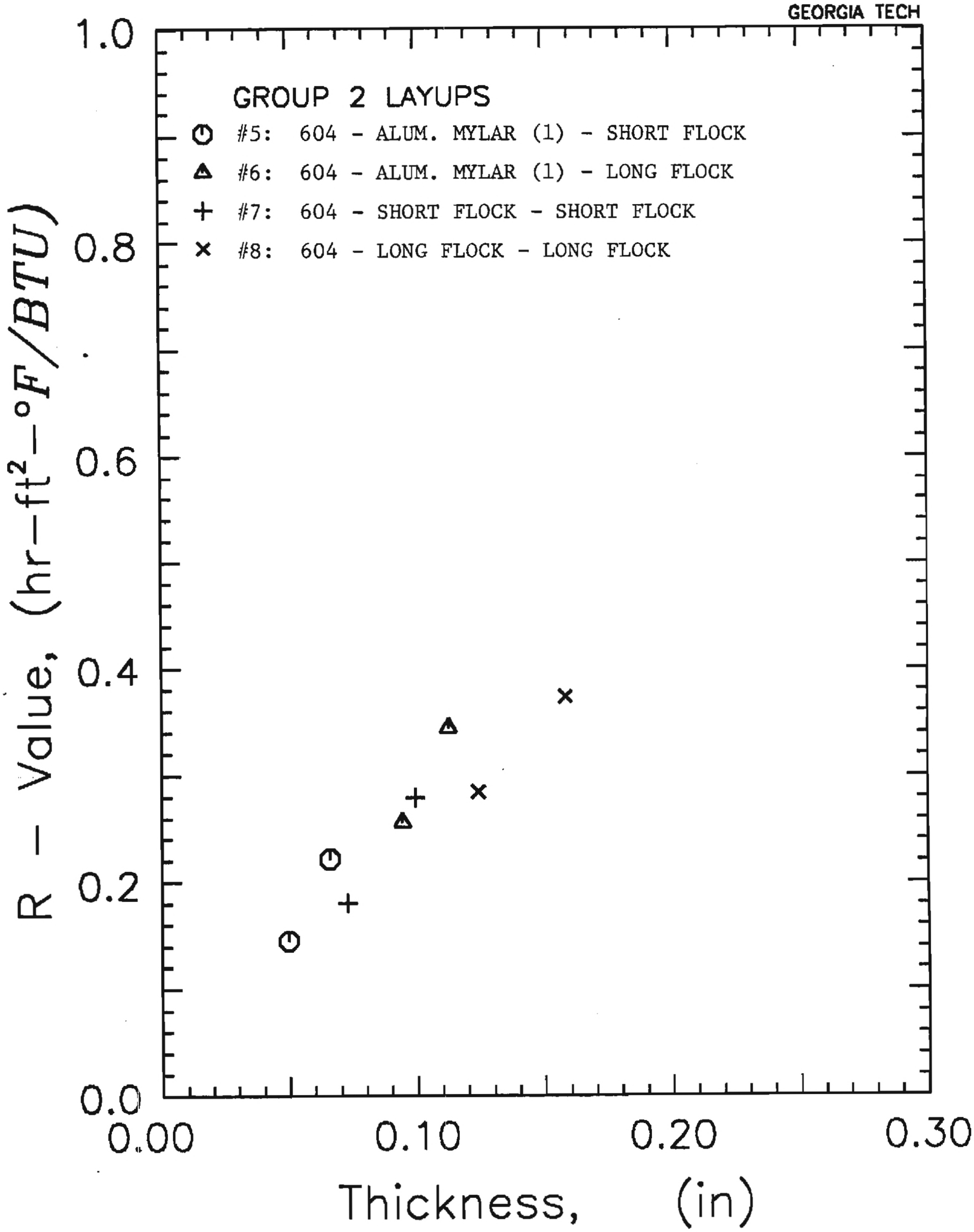

Figure C5. R Value vs. Thickness - Composite Layups, Group 2.

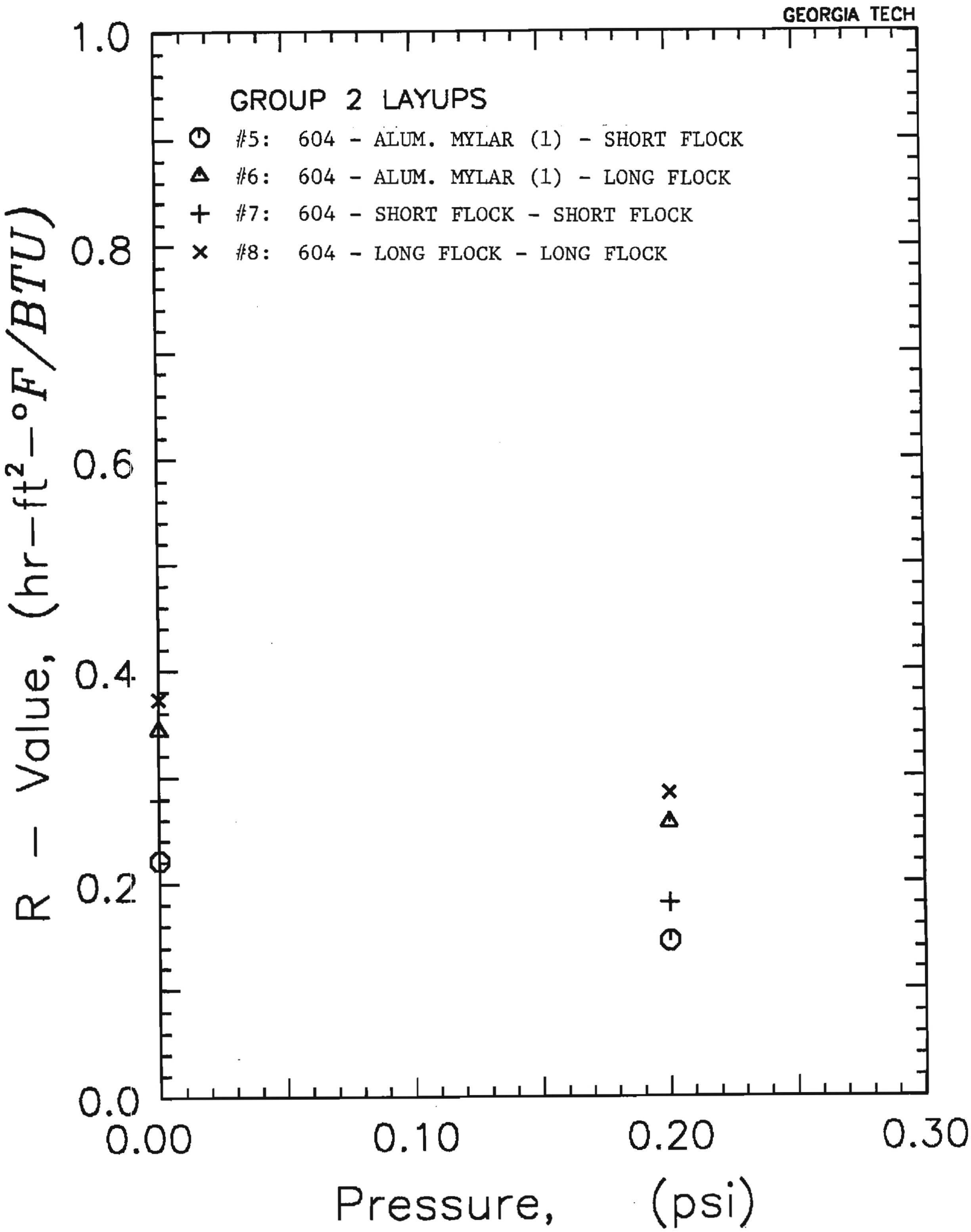

Figure C6. R Value vs. Pressure - Composite Layups, Group 2.

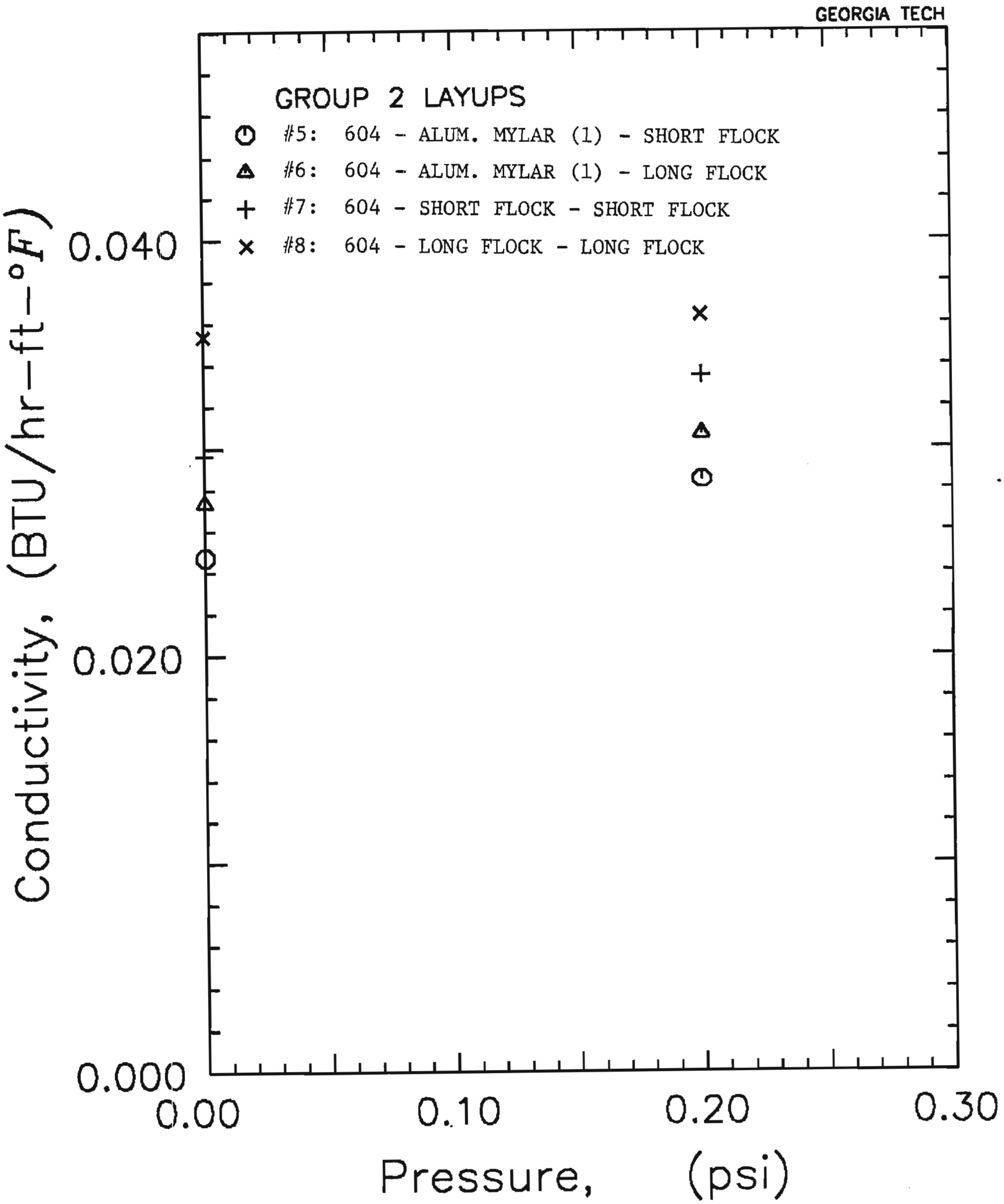

Figure C7. Conductivity vs. Pressure - Composite Layups, Group 2.

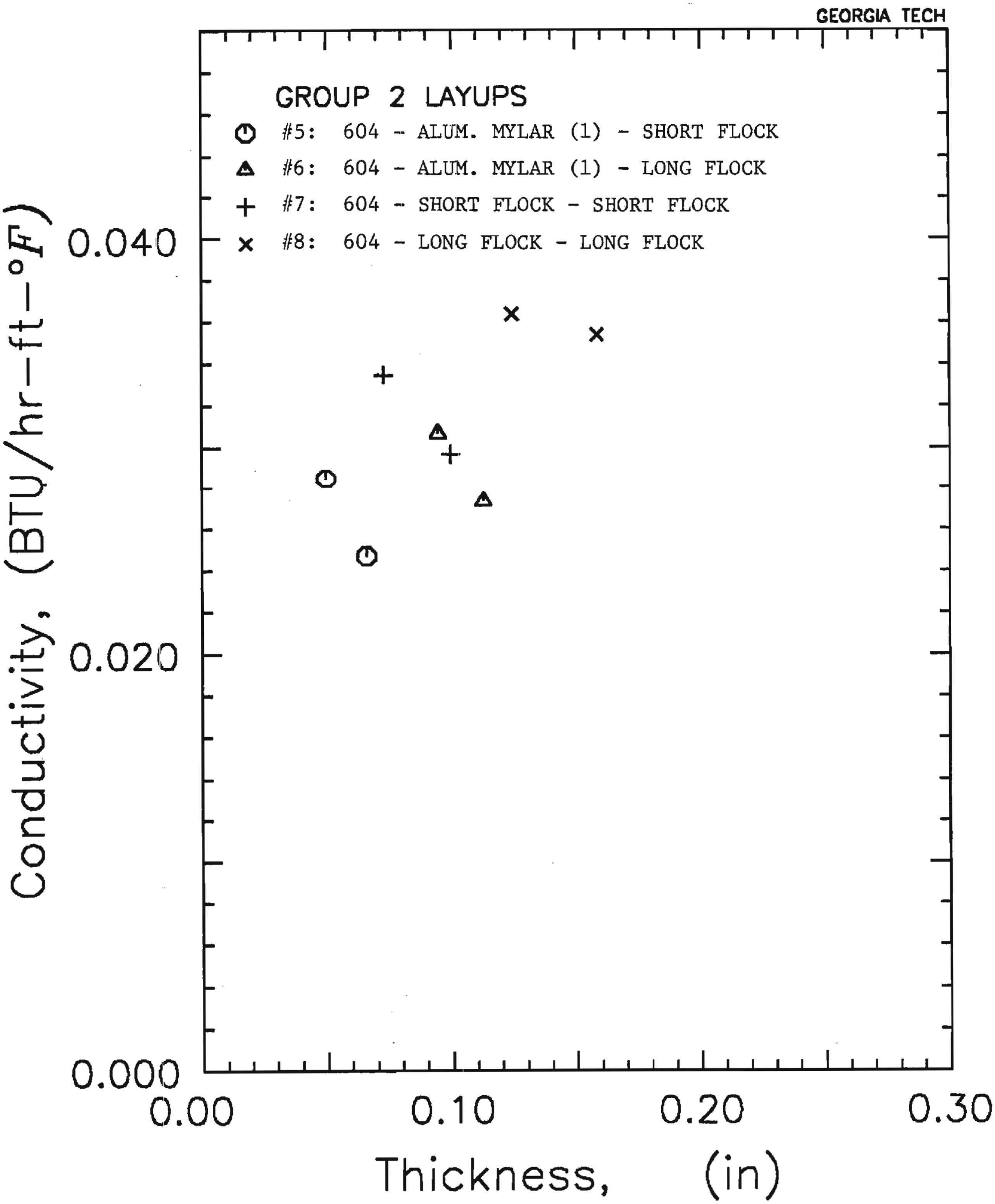

Figure C8. Conductivity vs. Thickness - Composite Layups, Group 2.

Table C3. Thermal Data - Composite Layups, Group 3.

APPLIED PRESSURE (PSI)	THICKNESS (IN)	T 1 (LOWER) (DEG C)	T 2 (UPPER) (DEG C)	HEAT FLUX (BTU/HR-FT2)	DEL T (DEG F)	CONDUCTANCE (FLUX/DEG F)	CONDUCTIVITY (FLUX*FT/DEG F)	R-VALUE (HR-FT2-DEG F/BTU)
TITLE FORMAT = (OUTER LAYER)-(MIDDLE LAYER)-(INNER LAYER)								
9. SAMPLE ID =		604 -TERRY-15364						
NOM	.2171	101.	68.	99.0	59.4	1.67	.030	.60
.200	.1550	100.	74.	114.0	46.8	2.44	.031	.41
10. SAMPLE ID =		604 -BLANKET-15364						
NOM	.2403	100.	63.	84.0	66.6	1.26	.025	.79
.200	.1825	100.	68.	95.5	57.6	1.66	.025	.60
11. SAMPLE ID =		604 -BLANKET-TMG LINER						
NOM	.2311	101.	63.	88.0	68.4	1.29	.025	.78
.200	.1786	101.	68.	96.5	59.4	1.62	.024	.62

* NOTE: "Blanket" refers to double flocked foam.

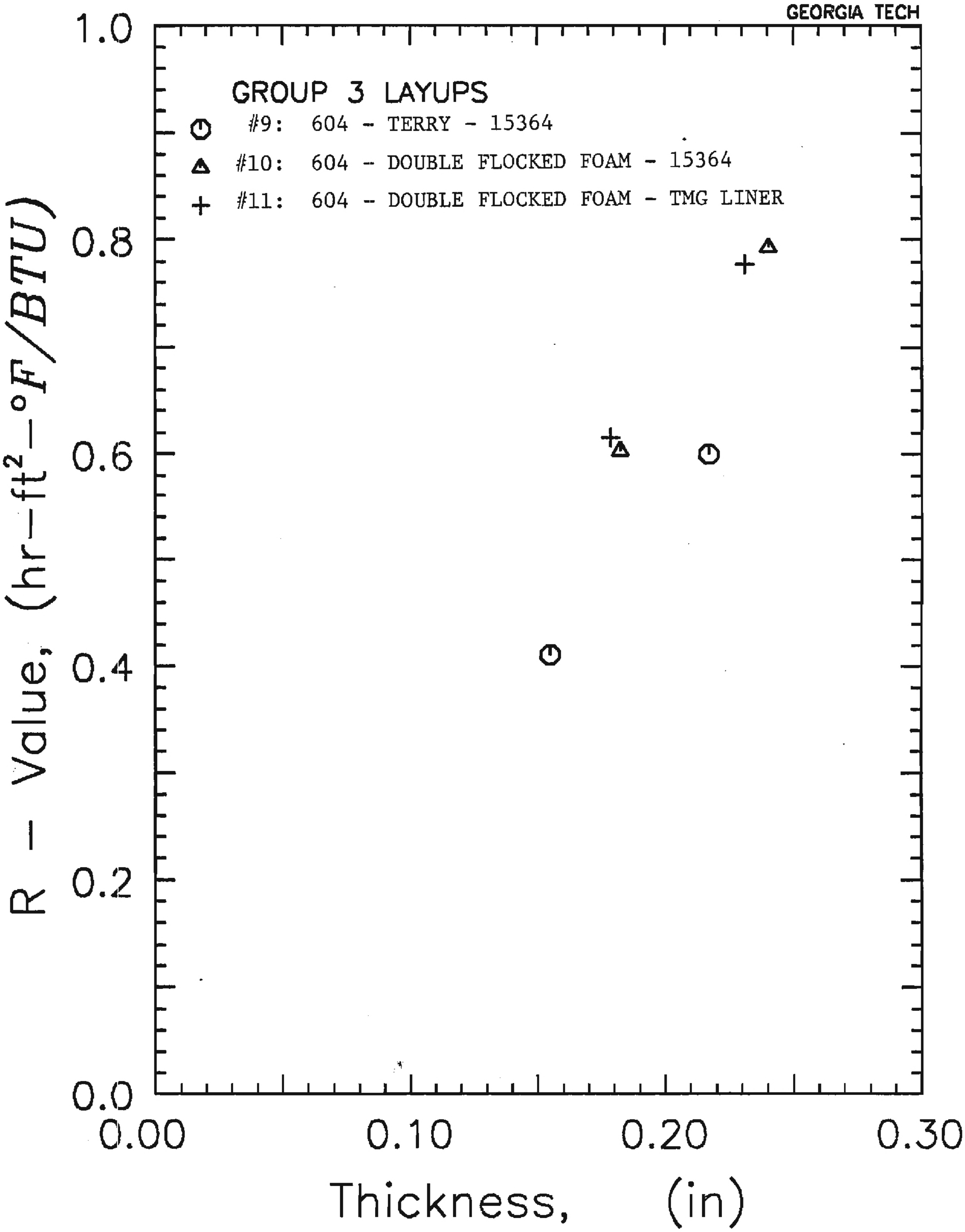

Figure C9. R Value vs. Thickness - Composite Layups, Group 3.

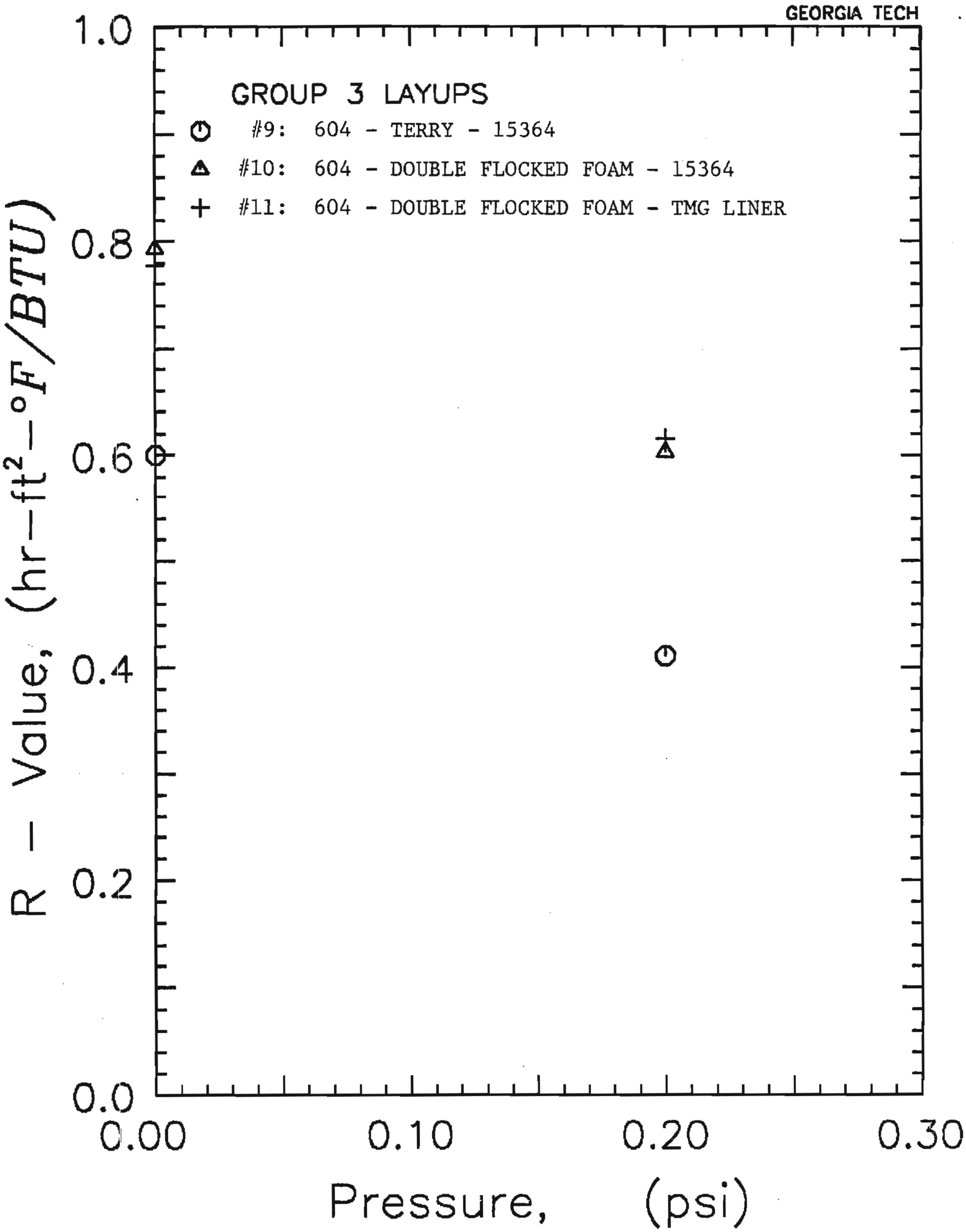

Figure C10. R Value vs. Pressure - Composite Layups, Group 3.

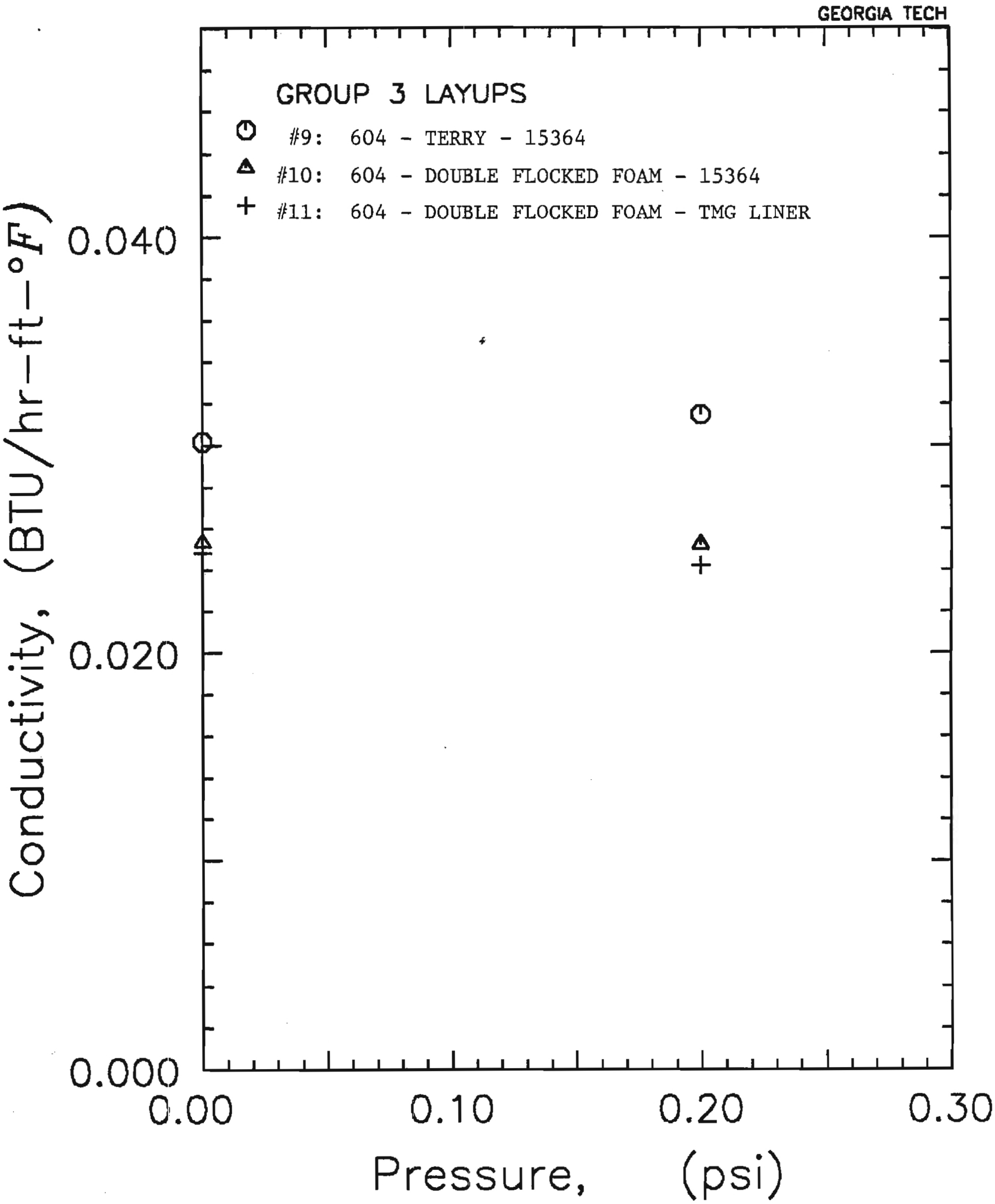

Figure C11. Conductivity vs. Pressure - Composite Layups, Group 3.

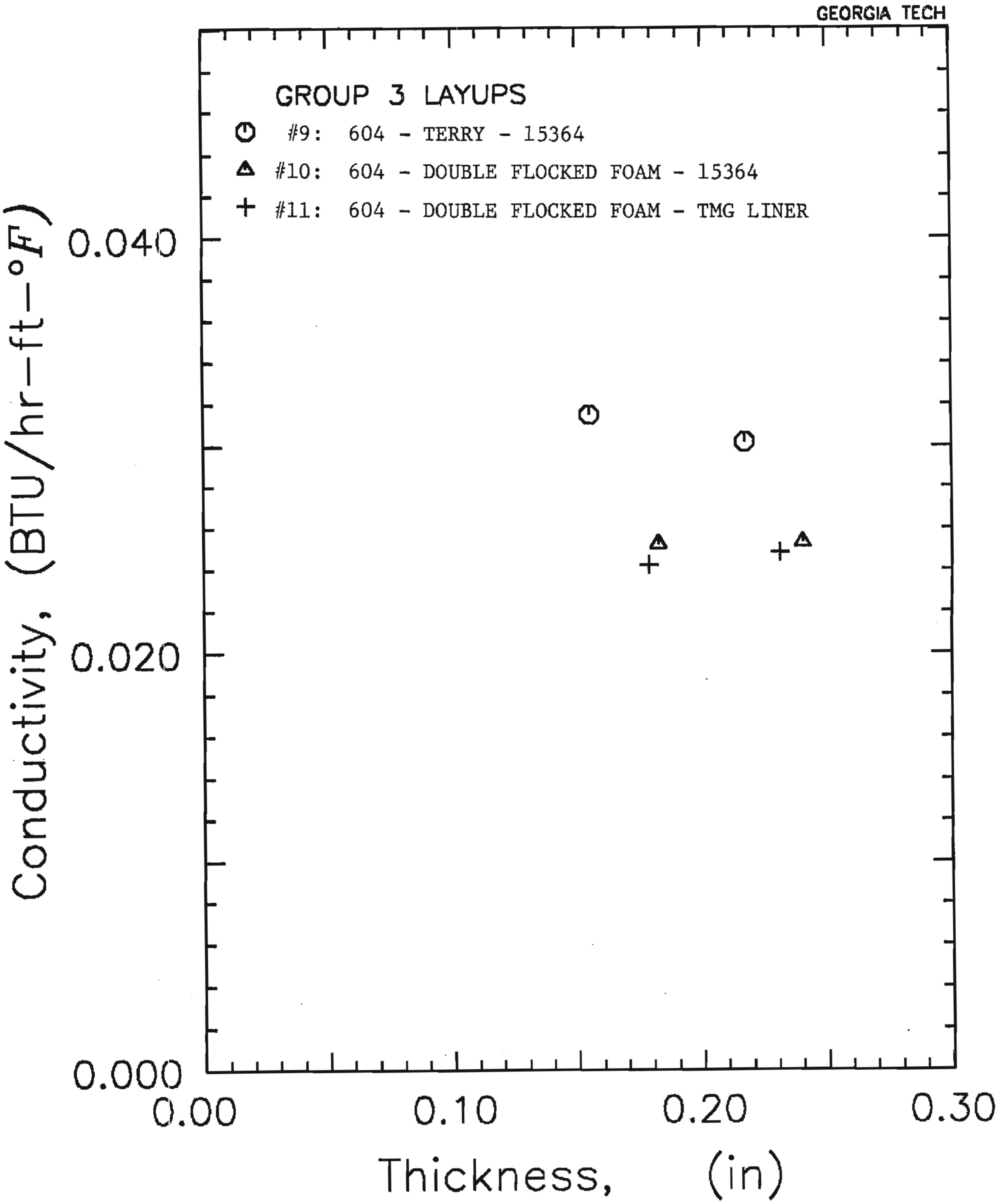

Figure C12. Conductivity vs. Thickness - Composite Layups, Group 3.

Table C4. Thermal Data vs. Pressure - Layup #4.

APPLIED PRESSURE (PSI)	THICKNESS (IN)	T 1 (LOWER) (DEG C)	T 2 (UPPER) (DEG C)	HEAT FLUX (BTU/HR-FT2)	DEL T (DEG F)	CONDUCTANCE (FLUX/DEG F)	CONDUCTIVITY (FLUX*FT/DEG F)	R-VALUE (HR-FT2-DEG F/BTU)
NOM	.1047	100.	78.	132.5	39.6	3.35	.029	.30
.050	.0950	100.	80.	137.0	36.0	3.81	.030	.26
.100	.0929	100.	81.	137.0	34.2	4.01	.031	.25
.150	.0912	100.	81.	138.0	34.2	4.04	.031	.25
.200	.0897	100.	82.	139.0	32.4	4.29	.032	.23
.250	.0885	100.	82.	139.0	32.4	4.29	.032	.23

Table C5. Thermal Data vs. Pressure - Layup #10.

APPLIED PRESSURE (PSI)	THICKNESS (IN)	T 1 (LOWER) (DEG C)	T 2 (UPPER) (DEG C)	HEAT FLUX (BTU/HR-FT2)	DEL T (DEG F)	CONDUCTANCE (FLUX/DEG F)	CONDUCTIVITY (FLUX*FT/DEG F)	R-VALUE (HR-FT2-DEG F/BTU)
NOM	.2403	101.	60.	91.0	73.8	1.23	.025	.81
.050	.2175	101.	62.	94.5	70.2	1.35	.024	.74
.100	.1993	101.	63.	100.0	68.4	1.46	.024	.66
.150	.1857	101.	64.	102.5	66.6	1.54	.024	.65
.200	.1810	100.	62.	102.5	68.4	1.50	.023	.67
.250	.1773	100.	62.	105.0	68.4	1.54	.023	.65

APPENDIX D

THERMAL DATA

TMG AND REPRODUCIBILITY

Table D1. Thickness vs. Pressure - TMG Cross Section.

Applied Pressure (psi)	Thickness (in.)	% Thickness	Density (gm/cc)
NOM	0.0828		
0.100	0.0693	100.0	0.5413
0.200	0.0637	91.9	0.5889
0.350	0.0610	88.0	0.6149
0.500	0.0582	83.9	0.6445
0.750	0.0557	80.3	0.6734
1.000	0.0532	76.7	0.7051
1.500	0.0513	74.0	0.7312
2.000	0.0495	71.4	0.7578
2.500	0.0483	69.7	0.7766
3.000	0.0470	67.8	0.7981

*NOTE: TMG cross section = composite layup #12 = 27.95 oz/yd^2.

Table D2. Thermal Data vs. Pressure - TMG Cross Section.

APPLIED PRESSURE (PSI)	THICKNESS (IN)	T 1 (LOWER) (DEG C)	T 2 (UPPER) (DEG C)	HEAT FLUX (BTU/HR-FT2)	DEL T (DEG F)	CONDUCTANCE (FLUX/DEG F)	CONDUCTIVITY (FLUX*FT/DEG F)	R-VALUE (HR-FT2-DEG F/BTU)
NOM	.1083	100.	73.	116.5	48.6	2.40	.022	.42
.050	.0764	99.	80.	135.0	34.2	3.95	.025	.25
.100	.0632	100.	84.	144.0	28.8	5.00	.026	.20
.150	.0564	99.	83.	147.5	28.8	5.12	.024	.20
.200	.0564	99.	84.	148.0	27.0	5.48	.026	.18
.250	.0548	99.	85.	149.5	25.2	5.93	.027	.17

Table D3. Thermal Data vs. Pressure - TMG Cross Section, Repeatability.

APPLIED PRESSURE (PSI)	THICKNESS (IN)	T 1 (LOWER) (DEG C)	T 2 (UPPER) (DEG C)	HEAT FLUX (BTU/HR-FT2)	DEL T (DEG F)	CONDUCTANCE (FLUX/DEG F)	CONDUCTIVITY (FLUX*FT/DEG F)	R-VALUE (HR-FT2-DEG F/BTU)
NOM	.1297	100.	67.	105.0	59.4	1.77	.019	.57
.050	.0680	100.	81.	139.0	34.2	4.06	.023	.25
.100	.0614	99.	82.	142.0	30.6	4.64	.024	.22
.150	.0505	99.	83.	142.0	28.8	4.93	.021	.20
.200	.0557	99.	84.	145.0	27.0	5.37	.025	.19
.250	.0545	99.	84.	145.5	27.0	5.39	.024	.19

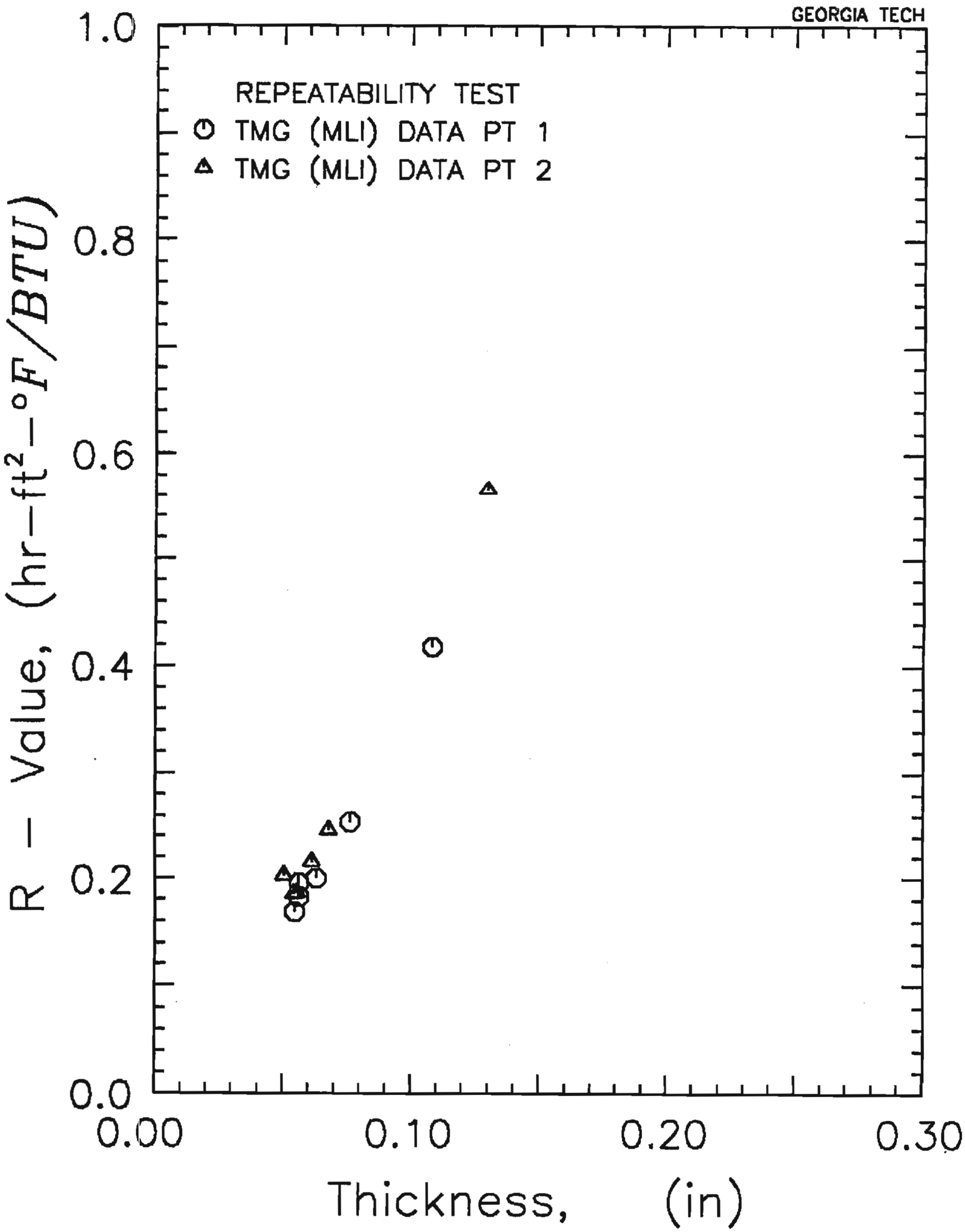

Figure D1. R Value vs. Thickness - TMG, Repeatability.

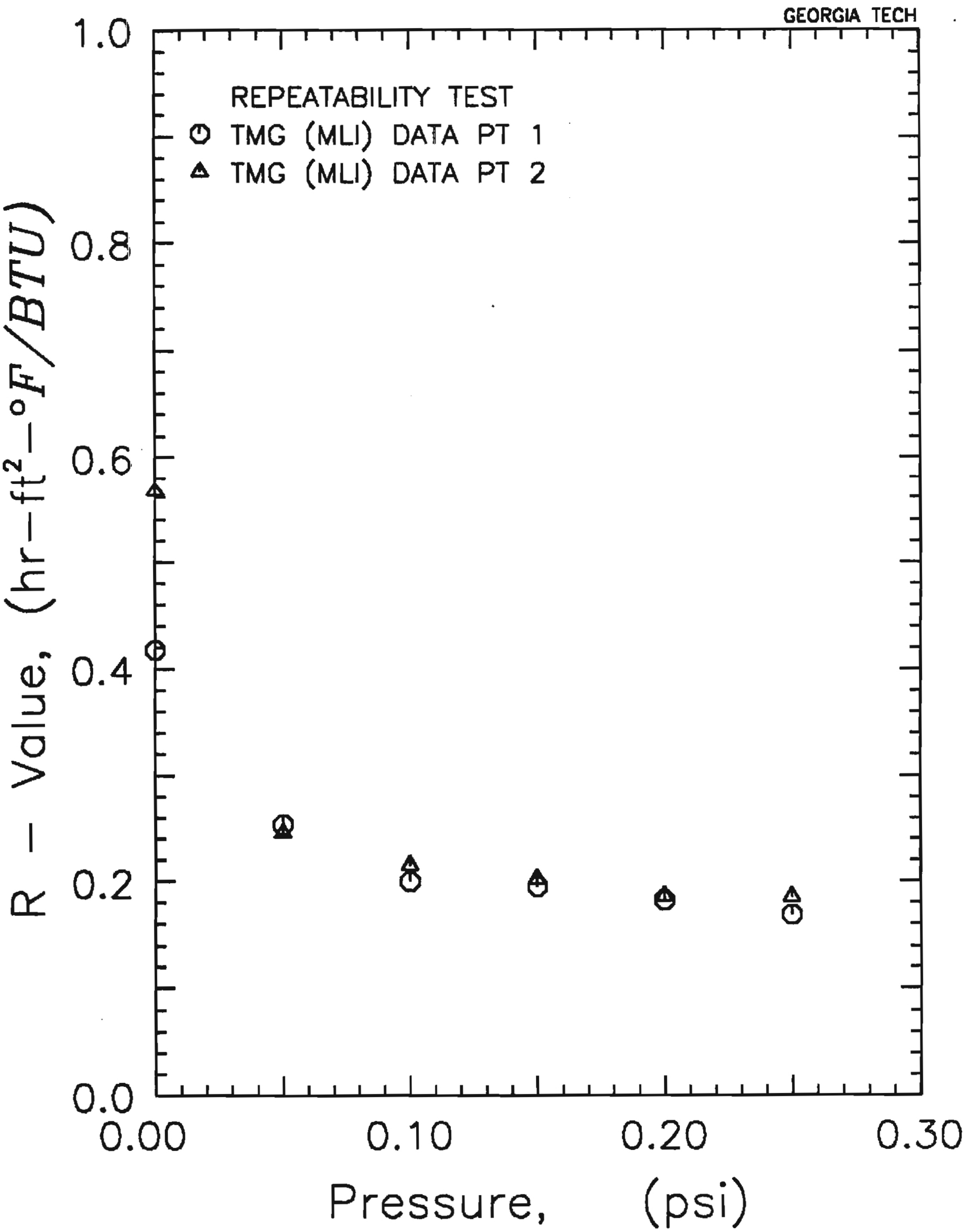

Figure D2. R Value vs. Pressure - TMG, Repeatability.

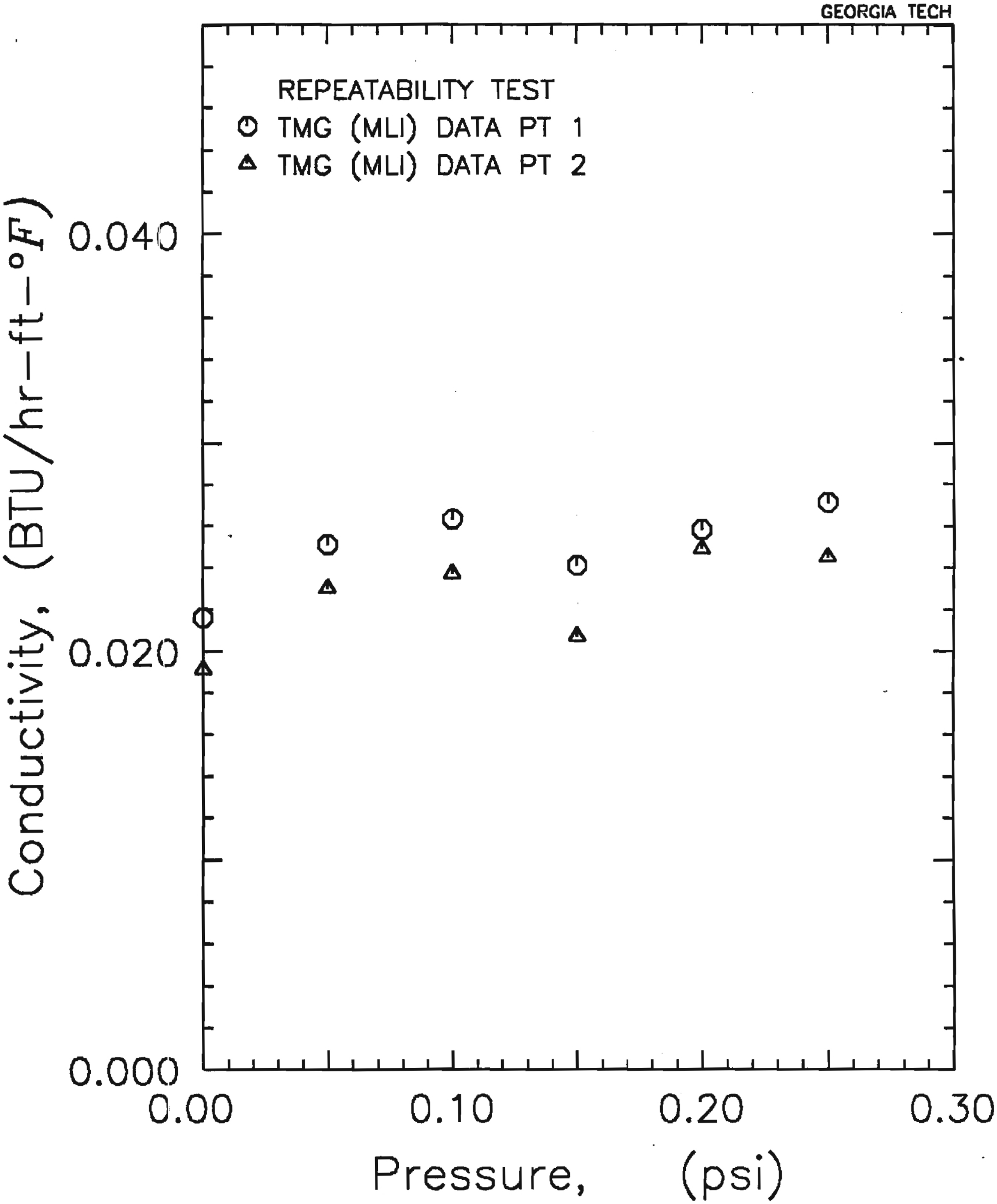

Figure D3. Conductivity vs. Pressure - TMG, Repeatability.

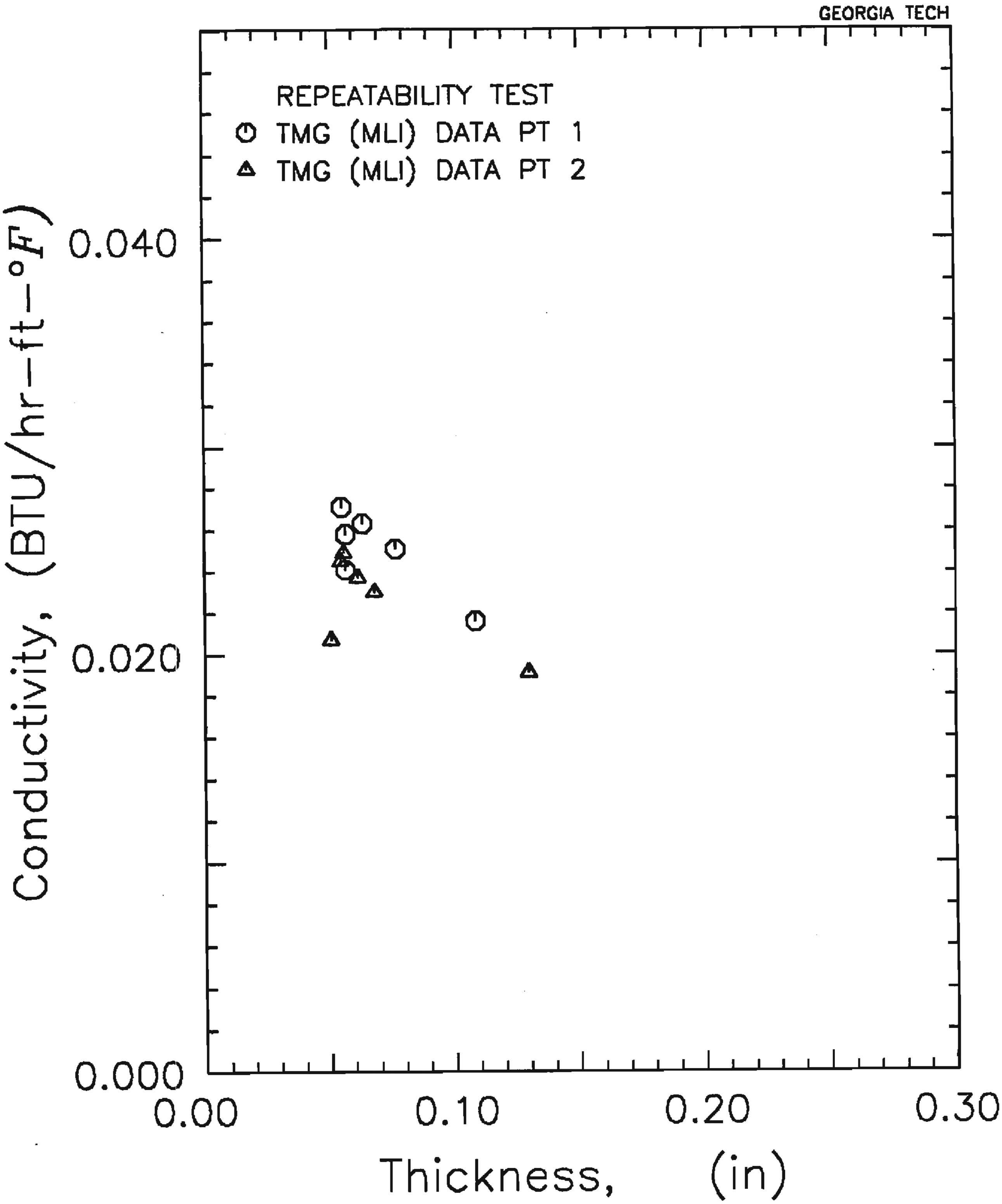

Figure D4. Conductivity vs. Thickness - TMG, Repeatability.

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